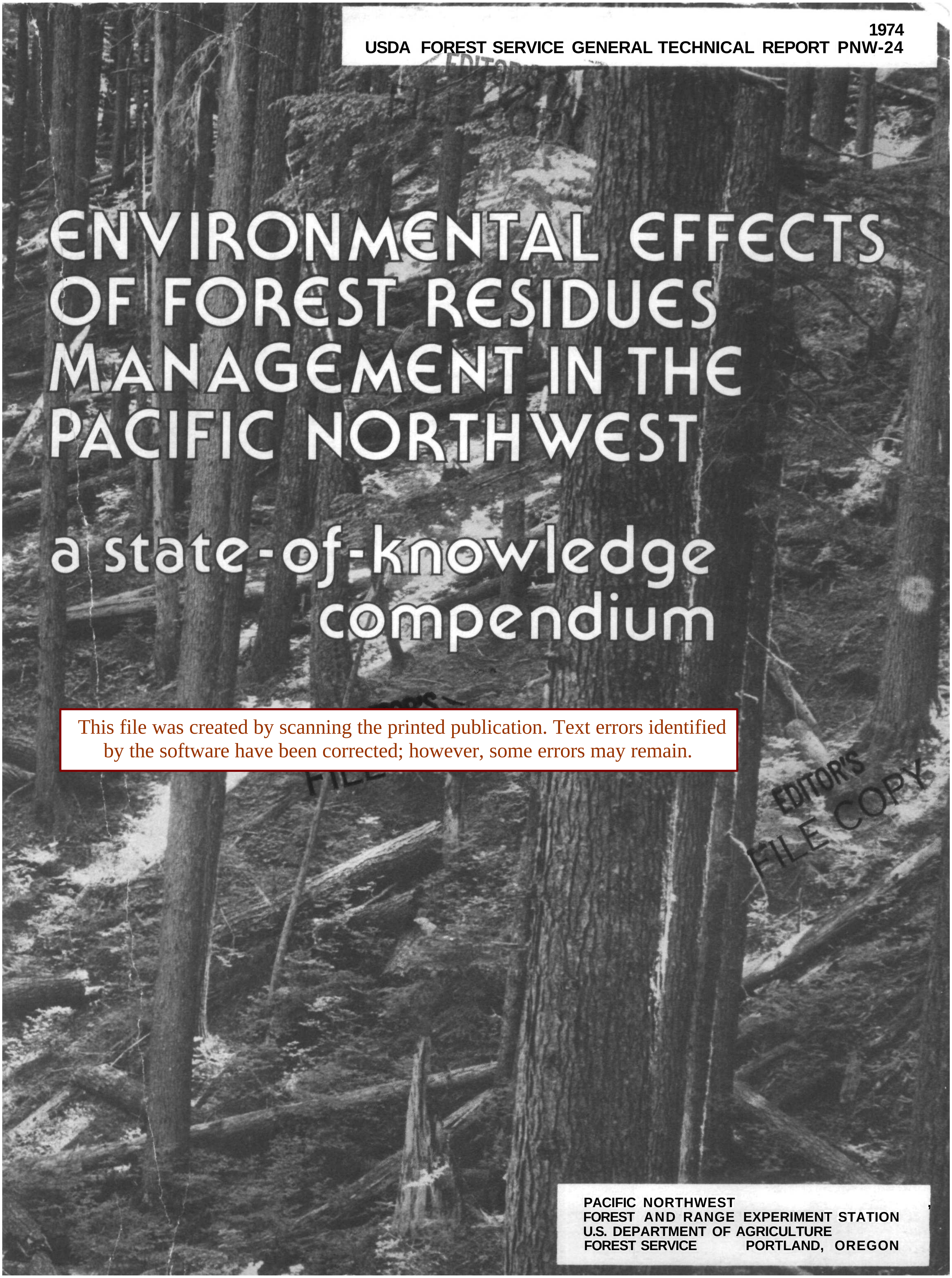
1974
USDA FOREST SERVICE GENERAL TECHNICAL REPORT PNW-24



ENVIRONMENTAL EFFECTS OF FOREST RESIDUES MANAGEMENT IN THE PACIFIC NORTHWEST

a state-of-knowledge compendium

PACIFIC NORTHWEST
FOREST AND RANGE EXPERIMENT STATION
U.S. DEPARTMENT OF AGRICULTURE
FOREST SERVICE PORTLAND, OREGON

ABSTRACT

Forest land generally produces considerable woody material other than that which is harvested as timber, needed for recycling of nutrients to the soil, or for sheltering wildlife and young forest seedlings. Excess forest residues, both living and dead, 'are often subject to treatment to reduce fire hazard, to eliminate obstruction to use and protection of the forest, and to remove unsightly accumulations of residue remaining after logging, road construction, or land clearing, or from thinning and pruning. The effects of these residues and of their treatment are frequently important, generally unmeasured, and are only poorly known. In this compendium, 27 research scientists have summarized the present state of knowledge of the effects of forest residues and residue treatments on the components of the forest environment: soil, water, air, fire, scenery, plant and forest growth, animal habitat, insects, and disease. In addition, they have questioned some current practices and have identified areas for research attention where current knowledge is lacking.

Keywords: Environmental effects; forest residues--brush, slash; forest residue treatment--mechanical, prescribed burning; silviculture; coniferae; Pacific Northwest; recommended research; fuel management.

For Sale by Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock No. 0101-00389

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USDA Forest Service General Technical Report PNW-24

ENVIRONMENTAL EFFECTS OF FOREST RESIDUES MANAGEMENT IN THE PACIFIC NORTHWEST

A State-of-Knowledge Compendium

OWEN P. CRAMER

Organizer and *Technical Editor*

1974

PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION

Robert E. Buckman, Director
FOREST SERVICE

Portland, Oregon
U.S. Department of Agriculture

FOREWORD

This Compendium is about the many important influences of natural and manmade forest residues on the forests of the Northwest. The creation of residues is a normal part of harvest cutting, thinning, right-of-way clearing, and other cultural activities. Whether we call it brush or forest fuel or slash is of little consequence. By any name it presents both a challenge and an opportunity to land managers. Forest residues may simultaneously represent a major conflagration potential, an esthetics problem, an important source of soil nutrient, a factor in the habitat of forest regeneration as well as wildlife, and a source of raw materials for forest industries. Considered up to now primarily as the forester's solid waste disposal and potential air pollution problem, residues management affects many facets of forestry.

It is time to take an integrated approach to both research and management of forest residues. In this Compendium we present a foundation of current knowledge on which the research and development work of our Forest Residues Reduction Program, already started, will continue to build. And forest managers will profit from decisionmaking aids currently being developed from this knowledge base; for example, guidelines for residue management in the forest environments of the Pacific Northwest are being compiled for publication in a separate document.

The effects of forest residues and their treatments should influence how the forest manager provides for forest regeneration and growth while maintaining the other biological, physical, and esthetic components of the environment. The current knowledge of these effects is covered in some detail in the chapters of this volume.

ROBERT E. BUCKMAN, Director
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PREFACE

Forest residues are increasingly important to the forest manager. They play a complex role as a source of soil nutrient, a fire hazard, an eyesore, an obstruction, a source of shade and shelter, a potential source of forest insect pests and possibly disease as well as air pollution or additional fiber. Natural forest residues have accumulated during the period of organized fire suppression resulting in increased conflagration potential in many areas. Public sensitivity to the esthetics of timber harvesting residue has become acute as has the general pressure to evaluate the impact on the whole environment of any manipulation of a portion of the environment.

This summary of present knowledge of environmental impacts of residues and the various treatments of residues will provide a basis for:

1. Guiding forest resource managers in their selection of residue treatment alternatives.
2. Planning an intensive, broad research and development program on effects of residue and residue treatments.
3. Designing equipment for treating forest residue.

Forest management policy, hence, residue management policy, is established on the basis of scientific, legal, social, and economic considerations. This Compendium will help provide a source of scientific information for consideration by lawmakers and policymakers. It might be considered a base for forest environmental quality "criteria."

Emphasis is on the effects of various kinds and treatments of forest residues on the environment; i.e., their physical and biological influences. Specifically not emphasized are value judgments related to official policy, law, custom, or social value. Also avoided are:

1. Effects of cutting area layout or logging method.
2. Utilization practice and potential.
3. Economics of either the residues or their treatments.

Both the concept and knowledge of the effects of forest residues are in a state of development. The very definition of forest residues has changed during the formulation of the research and development program sponsoring this Compendium. At first, the definition included only slash; now it encompasses both living and dead, mostly unwanted, woody materials that accumulate naturally on the forest floor or are left after timber harvesting. Little research has been conducted to determine the optimum amount of residue needed to maintain or improve soil conditions for best regeneration survival and growth or to present a "natural" appearance. The amounts and kinds of residue that comprise a maximum tolerable fire hazard have not been determined. The effects of alternative residue treatments on the component forest resources such as soil and trees are only partly known.

Residues represent both negative and positive environmental values and, to management, may be both an impediment and an environmental variable that can be manipulated to advantage. A heterogeneous association of residues may comprise: (1) a fuel complex which could sustain conflagrations; (2) an intricate arrangement of materials which stabilizes soil and sustains continuing growing capacity; **(3)** a composite of dead and living material which furnishes the habitat not only for game animals and fish but even for the microflora and microfauna so essential to the forest ecosystem.

Environmental management of forest residues involves much more than disposal or utilization. To adequately specify and meet environmental management requirements, we must organize present knowledge in a workable decision frameyork. Specific elements of knowledge needed for such a framework are assembled herein. Although no attempt is made to quantify cost and benefit values, or more important, to evaluate the trade-off compromises that must often be made, the authors have tried to identify the residue conditions and effects that clearly are environmentally unacceptable.

The reader will encounter apparent contradictions between authors. This is to be expected since individual contributors address themselves to different environmental components and to different management goals and constraints. In some cases, there may appear to be no really acceptable alternative. This is to be expected when goals are unrealistic or knowledge is lacking.

To prepare this Compendium, the authors, specialists in many disciplines, have put aside their immediate duties to explore the pertinent literature, to summarize their personal knowledge, to appraise present practices, and to suggest research aimed at resolving unanswered questions. They have been thorough in identifying voids and disparity while recording documented knowledge and expert opinion in many fields. To these author scientists we are greatly indebted.

We gratefully recognize the assistance of the San Dimas Equipment Development Center engineers who, in seeking this type of reference source for design considerations, have funded part of the cost and assisted with the difficult task of critique.

Special acknowledgment is due other scientists who have contributed to the technical accuracy and applicability of this Compendium:

Weyerhaeuser Timber Company
- Norman E. Johnson
- Paul G. Lauterbach
- William D. Lawrence
- Rudolph N. Thut

Oregon State University, Corvallis
- George W. Brown
- Henry A. Froelich
- Michael Newton

University of Washington, Seattle
- Charles H. Driver
- Robert I. Gara
- Richard D. Taber

University of California at Riverside
- Ellis F. Darley

Washington State University, Pullman
- Don Adams
- Richard W. Dingle.

University of British Columbia, Vancouver
- James D. Hall

Canadian Forest Service
- Gordon W. Wallis

Oregon State Department of Forestry
LeRoy N. Kline

U.S. Forest Service

Northeastern Forest Experiment Station, Upper Darby, Pennsylvania
C. Anthony Federer

Intermountain Forest and Range Experiment Station, Ogden, Utah
Dale O. Hall
Harold F. Haupt
James E. Lotan
Robert C. Lucas
L. Jack Lyon
Con H. Schallau

Northern Forest Fire Laboratory, Missoula, Montana.
Hal E. Anderson
Robert E. Benson
James K. Brown

Pacific Northwest Forest and Range Experiment Station, Portland, Oregon
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Charles T. Cushwa
C. Theodore Dyrness
Richard L. Fredriksen
William R. Meehan
Richard E. Miller
Don Minore
Logan A. Norris
Stewart G. Pickford
Dale R. Potter
Kenneth W. Seidel
Roy R. Silen
Ron E. Stewart
John C. Zasada

Pacific Southwest Forest and Range Experiment Station, Berkeley, California
Henry W. Anderson
Lisle R. Green

Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado
Charles C. Avery
Thomas E. Hinds
Hudson G. Reynolds

Southeastern Forest Experiment Station, Southern Forest Fire Laboratory, Macon, Georgia
James A. Pharo

Northern Region, Missoula, Montana
William R. Beaufait

Pacific Northwest Region, Portland, Oregon
Robert E. Dolph
Howard E. Graham
Asa D. Twombly

Environmental Protection Agency
Gerard A. DeMarrais
Raymond G. Wilhour

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Store pesticides in original containers under lock and key--out of the reach of children and animals--and away from food and feed.

Apply pesticides so that they do not endanger humans, livestock, crops, beneficial insects, fish, and wildlife. Do not apply pesticides when there is danger of drift, when honey bees or other pollinating insects are visiting plants, or in ways that may contaminate water or leave illegal residues.

Avoid prolonged inhalation of pesticide sprays or dusts; wear protective clothing and equipment if specified on the container.

If your hands become contaminated with a pesticide, do not eat or drink until you have washed. In case a pesticide is swallowed or gets in the eyes, follow the first-aid treatment given on the label, and get prompt medical attention. If a pesticide is spilled on your skin or clothing, remove clothing immediately and wash skin thoroughly.

Do not clean spray equipment or dump excess spray material near ponds, streams, or wells. Because it is difficult to remove all traces of herbicides from equipment, do not use the same equipment for insecticides or fungicides that you use for herbicides.

Dispose of empty pesticide containers promptly. Have them buried at a sanitary land-fill dump, or crush and bury them in a level, isolated place.

NOTE: Some States have restrictions on the use of certain pesticides. Check your State and local regulations. Also, because registrations of pesticides are under constant review by the Federal Environmental Protection Agency, consult your county agricultural agent or State extension specialist to be sure the intended use is still registered.

PROTECT
Use Pesticides Safely
FOLLOW THE LABEL
U.S. DEPARTMENT OF AGRICULTURE

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*Unless otherwise identified in article. authors are with the Pacific Northwest Forest and Range Experiment Station.

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G.M. Jemison[1/] and Merle S. Lowden[2/]

ABSTRACT

This article introduces 18 state-of-knowledge papers that follow on specific components of the forest environment. The quality of the forest environment is closely tied to the presence, kind, distribution, and amount of residue, hence, to residue management. The unwanted woody material, living or dead, that accumulates on forest land is scrutinized from the standpoints of its biological, physical, and socially oriented impacts on the environment. Effects of forest residue treatments are similarly reviewed. Related important considerations of economics, utilization, logging, and roadbuilding are specifically omitted. Residue management must become an integral part of the total resource management program, and suggestions are presented for utilizing present knowledge of residues and treatments to achieve this goal in resource management decisionmaking. Preparation of forest residue management guidelines is described. These guidelines, with the knowledge summarized in the 18 papers, should help experienced public and private forest managers solve critical residue problems. The high-priority research and development needed to provide an expanding foundation for intensifying residue management are also highlighted.

Keywords: Environmental effects; forest residues--brush, slash; forest residue treatment--mechanical, prescribed burning; silviculture; coniferae; Pacific Northwest; recommended research; fuel management.

INTRODUCTION

A typical forest environment contains a complex of living and dead vegetation created by natural forces and often modified by man. Trees and lesser plants grow and die, their lifespans sometimes affected by wind, fires, insects, diseases, or other events. Man harvests trees, builds roads and trails,

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powerlines, ski runs, and other improvements necessary to develop, manage, and use the forests. Some forest areas become occupied by unwanted brush or tree species. All of these natural and man-generated events create forest residues--the unwanted, mostly woody material both living and dead that accumulates in the forest.

Although forest residues sometimes benefit the development and use of the multiple resources of the forest, they also can impede attainment of an individual's, a group's, or society's objectives. Resource managers need to understand how residues and their treatment influence the environment. They must be able to choose wisely among management alternatives affecting residues and to select the course of action that most nearly brings them closest to their objectives for all components of the environment.

In this beginning chapter, we shall develop an overview of what is known about the forest residue problem and the management implications of man's attempts to do something about it. We are especially concerned with environmental impacts and how an understanding of the interplay of environmental components can be used to improve forest management programs and even to form a basis for balanced environmental laws and regulations.

The documentation on which this Compendium rests *is* limited to environmental influences of residues. It specifically does not include discussions of the economic and utilization aspects of residue management which we recognize to be essential elements in solving residue management problems. Although we touch on the importance of economic considerations to the decisionmaker and on utilization as a means of lessening residue problems, a full discussion of these factors is beyond the established scope of this Compendium.

The body of this volume contains 18 technical papers, each of which summarizes current knowledge of one component of the environment as it is affected by residue and residue management. We cannot condense in this chapter all the information contained in the 18 papers. The reader is urged to search this Compendium for detailed treatment of what is known and not known about each aspect of the residue problem.

In this chapter we discuss the following specific subjects:

- Character of the residue problem--its importance as an element in maintaining an acceptable environment.
- Knowledge available concerning the biological, physical, and socially oriented impacts of residue occurrence and treatment on the environment--a highlight summary.
- Applications of current knowledge to help the resource manager in decisionmaking.
- High priority research and development needs for making residue management more effective.

Throughout this chapter we will not cite the source of technical statements or generalizations on residue problems and residue management. These all come from the 18 supporting papers or from personal experience of the authors.

THE FOREST RESIDUE SITUATION

Residue is a natural product of the forest that may be added to, rearranged, or reduced by man's management. Since the beginning of time, nature has handled residue in its own way. Tree limbs die and drop to the ground. Undergrowth is shaded out and dies. Windstorms uproot trees. Insects and diseases add their toll to natural accumulations of residue. Needles, leaves, and twigs build up on the forest floor. All such organic materials gradually decompose to contribute to the soil formation process. Other natural forces, such as lightning-caused fires, destroy residue and also bring about changes in the forest complex.

As nearly as can be deduced from the accounts of early explorers, from stump ring counts that date fire scars, and from the patterns of forest ages, fire was no stranger to Northwest forests. Particularly east of the Cascades, lightning apparently started fires that every few years burned off the forest floor as soon as there was sufficient residue to sustain spread. The result was comparatively light fires that removed residue and left open forest and grassland with little brush or excessive reproduction. Since man has extinguished these fires, live and dead residues have accumulated and even the forest composition has changed. Wildfires have become more severe, and forest management is faced with extensive problems of thinning and invasion by less desirable species. There may be some lessons for ponderosa pine culture in the natural periodic underburns of the past.

West of the Cascades lightning was less frequent, but the American Indians annually burned much of the flat valley areas as part.of their harvesting of wild foods and apparently also to improve visibility for hunting and detecting possible enemies. These fires occasionally spread into forests of the Coast and Cascade Ranges where residue accumulation was often great, much as it is now. The result was destructive wildfire that killed the forest and set up conditions for regeneration of a new even-aged forest..

When the West was developed, forest products were needed in vast quantities for homes, schools, railroads, and other structures. Extensive forest areas were cut over. Slash created by logging was largely ignored, and disastrous fires often followed. But logging slash has gradually been recognized as only part of the problem.

WHY A PROBLEM EXISTS

In recent years forest residue has come sharply to the attention of the general public and has become a concern to many people. What was once just brush, slash, or trash has suddenly become an eyesore, a source of water pollution, and the setting for damaging forest fires that cause smoke and haze or other undesirable effects on the environment. The many undesirable impacts associated with residue bewilder and alarm many individuals. Informed organizations such as trail or hiking clubs, wildlife groups, the Sierra Club, the Wilderness Society, and others interested in the out-of-doors, are concerned. Combatting the adverse effects of forest residues, particularly those associated with logging, is an important part of their programs.

Many demands have been made on legislators--national , State, and local--to prevent or cure the environmental problems that people fear. From the many pressures and drives at the national level have come the Council for Environmental Quality and Environmental Protection Agency. At the State and local levels there are various counterparts in the form of environmental quality agencies. Such control or management agencies have many laws and regulations to enforce in an endeavor to cure the environmental problems by law. Regular or old-line agencies at the various government levels also have a host of new rules or laws to enforce on environmental quality. Relatively few of these legal restrictions are directly concerned with forest residue, but the number is increasing.

Forest resource managers recognize that the most commonly expressed environmental concerns of the people relate to the quality of air, water, and scenery. But the managers also know that less understood impacts of residue on soil, water, fish and wildlife habitat, and even long-term timber production capabilities are important. They realize that single purpose residue treatments will not always accomplish balanced environmental needs.

Smoke from residue disposal by burning is a small part of the emissions from man's activities that degrade air quality with gases and particulates. Forest residue smoke has attained more than normal attention in the Northwest because of the large logging slash burning program concentrated in a short period of the year. In Oregon, the concern has been accentuated by the large, field burning program on grass seed-producing farms in the Willamette valley, This annual program has brought about restrictive State rules culminating in an absolute prohibition of open field burning set for 1975.

Under the pressure of public concern and the possibility of a similar prohibition on burning logging residue, fire protective agencies developed smoke mangement programs in cooperation with the State environmental quality agencies in Oregon and Washington. These programs provide for burning forest residues only under combinations of times, places, weather, and amounts that keep smoke away from population concentrations, as in the larger cities. Under such plans, owners or operators burn only when they are notified that current weather situations meet prescribed conditions.

All smoke from forest residue burning is not from logging slash disposal, but this is by far the greatest source. Formerly, much sawmill waste was burned in "wigwam" burners which have generally been outlawed. Much of the sawdust, chips, and slabs formerly wasted is now used for pulp manufacturing; but some merely accumulates as solid waste. The waste disposal problem at millsites can be aggravated by programs that stimulate the logging and transport of excessive cull material when alternatives for disposal of unusable material are limited.

Burning continues to be a chief means of disposal of residue from clearing of roads, power rights-of-way, reservoirs, farms, and many other areas. Usually, these activities are not as concentrated at one period of the year as is logging slash burning, but they still contribute to the total problem and are regulated. Advanced air pollution control programs strive for as complete combustion as possible. Such objectives influence the plans for methods of burning as discussed later in this chapter.

Most visitors to forest areas want naturalness, and residue accumulations are often considered an unwelcome deviation from the natural scene. Generally, manmade residue is considered worse than that from natural or natural-appearing causes. Logging slash is thus considered by many as particularly offensive from an esthetic standpoint. People's esthetic reactions to residue are affected by many factors, such as how closely they view debris, how keen they are as observers, and how much they know about forest management. Unquestionably, untreated logging residue along highways or heavily traveled roads has been one of the chief factors causing people to criticize all logging and especially clearcutting.

Most people are particularly critical of what they believe is waste. They object if logs or larger materials are left in the woods even though they may not be sound or of sufficient value to pay the cost of removing and processing them. Such concern for waste is growing because of the increasing scarcity of wood products, their higher costs, and decreasing commercial timberland base. In the face of these problems, people ask why more of the material in forests is not being used. Such questions provide mounting challenges for forest managers.

CHARACTERISTICS OF RESIDUE

In this Compendium, forest residue is defined as the unwanted, generally unutilized accumulation in the forest of woody material, including litter on the forest floor, that originates from activities of man such as timber harvesting, land clearing, and cultural practices, or from natural processes. Unwanted living brush and weed-tree species are also considered residue if their presence prevents growing more useful species. Residue may be an intolerable obstruction to management, a fire hazard, or an eyesore. Residue problems exist in natural stands due to excessive accumulation from self-pruning and mortality of trees or from catastrophic events.

Harvesting operations produce large amounts of residue, but so do many' cultural operations. In precommercial thinning, small trees, tree limbs and tops are left just as limbs are left after pruning. Clearing for roads, trails, utility lines, reservoirs, agriculture, improvements, and for other purposes also results in residues.

Natural residues result when trees or other vegetation are killed by insects, diseases, fire, lightning, wind, freezing, drought, or other weather conditions. The natural dying of lower limbs and the killing of trees through overcrowding produce residue. Residue may occur in many isolated locations as single insect-killed trees, or it may be in large continuous areas as those burned by fires, struck by disease epidemics like chestnut blight, or devastated by an insect such as tussock moth.

Residue from logging gets the most attention because of the large volume, the vast area covered, and its visibility to many people. Logging slash has received major attention in the Northwest for many years because of its effect on the fire problem. Many of the most damaging fires in the region start or spread in slash areas. This applies particularly to the Douglas-fir region on the west side of Oregon and Washington where clearcutting produces volumes of residue ranging from 40 to 227 tons/acre (90 to 508 metric tons/ha) according to 1971 measurements.

Although precise statistics are not available, some approximations will indicate the magnitude of the logging residue disposal effort in Oregon and Washington. In the 1962-64 period, clearcut logging slash on all ownerships in the two States was broadcast burned on 128,000 acres (51,800 ha) annually and piled and burned on 126,000 acres (50,991 ha) annually. Since then, broadcast burning on National Forests has decreased 40 percent, and pile and burn acreage has increased 50 percent. Part of this change is due to a shift from clearcutting to partial cutting on the National Forests. In 1970, 59,660 acres (24,144 ha) were clearcut, 440,935 acres (178,443 ha) were partially cut, and 53,254 acres (21,552 ha) were precommercially thinned. Currently, 2,377,448 acres (962,140 ha) of slash is carried over from previous years for treatment or extra protection, and this total is growing.

For various reasons, mostly legal, logging residue is not being abated--it is accumulating; and this is true of all ownerships. On National Forests, though utilization may be improving, only 15 percent of the acreage of slash created is actually treated. This is of particular concern to fire people because untreated clearcut areas require from 15 to 20 years before fire hazard approximates fuels on similar but freshly broadcast-burned areas. In the drier climate east of the Cascades, deterioration is much slower.

Several current trends are affecting the amount of residue in the forests. Increased values of forest products and the great demand for timber are bringing about better utilization. Better roads, new and improved harvesting equipment, and forest product utilization research have stimulated residue removal. Many private owners now harvest small-size and low quality material generally considered unusable in the past. This practice reduces the residue left on the ground. The public has demanded better cleanup from an esthetic standpoint along roads and in viewed areas. Through a system of yarding unutilized material, called "YUM,"[3/] large material is yarded into piles near or on roads. When thus made accessible, more of it is being used though most YUM piles are still burned. On the other hand, environmental constraints have reduced the amount of slash burning; therefore, more slash is left in many places.

Although natural processes regularly produce residues, the major residue-producing catastrophes get the attention and cause the greatest problems. Large fire-killed stands, if not salvaged are a management problem for many years. Snags are a major fire worry because if ignited, they spread fire readily. Establishment of new forests in snag areas carries a high risk. Large areas of mortality caused by insects or diseases present similar problems, but these have not occurred so often nor are they widespread. An exception is the vast kill by tussock moth in northeast Oregon.

Although improved fire protection in recent years has reduced the acreage burned, at the same time it has caused a steady accumulation of natural residue throughout Northwest forests. This residue is becoming of much concern to fire management officers and has led to trials in prescribed burning and to the practice of letting wildfires spread under surveillance in some areas under limited conditions.

Various combinations of events such as repeated forest fires that eliminated seed sources of desirable forest tree species have resulted in occupation of some 4-1/2 million acres (1.82 million ha) of commercial forest land in the Pacific Northwest by brushfields or weed trees. Much of this vast acreage is needed for

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3/ Hereafter in this chapter we shall refer to this practice as "YUM" or "YUMing."

forest production. The conversion process is primarily residue management--removal of the living residue in such a way as to provide soil and habitat conditions that will favor establishment of conifers.

The above paragraphs emphasize the undesirable aspects of natural and manmade residues. However, one should also understand the importance of forest residues in maintaining a healthy and balanced environment. As forest vegetation picks up and incorporates mineral nutrients and nitrogen from the soil, it returns these elements for recycling through death, litter fall, and decay processes, accelerated by logging and other activities of man. Residue performs many functions in the environment beneficial to wildlife, water supplies, and tree growth; these benefits are discussed fully in other Compendium papers.

METHODS FOR DEALING WITH RESIDUE

Many methods of treating forest residue, particularly those resulting from timber harvesting, have been applied in the Pacific Northwest. The principal purpose has usually been to lessen the fire hazard, although seed bed preparation, removal of obstacles to planting, cleanup from a scenic standpoint, rehabilitation of stream channels, and other reasons are important. Large residue material may be reduced by utilization for a salable product. Residue may also be disposed of or changed in physical form by mechanical means.

Finally, it may be left without treatment and subject only to the natural decomposition processes. Varying environmental conditions and objectives indicate different treatments. Some have long been standard practice, but others are still developmental. Each treatment has its own characteristics.

BURNING

The chief means of treatment has been with fire either over an entire cutting area or in selected locations with or without some effort at concentration of the residue. Burning has not been practiced on all ownerships nor on all areas of the same owners. Some owners have been categorically against any burning of cutover areas. Others who generally favor burning will sometimes forgo the use of fire because of a stand'of advance reproduction, high burning costs, slight fuel loading, unfavorable burning conditions, or other reasons.

Several residue disposal methods involving burning are used. In most cases, the use of fire is "prescribed," involving careful planning and determination of specific weather and fuel conditions to create a predetermined effect. Thus, "prescribed fires" are confined in area, regulated in intensity, and otherwise controlled to achieve the environmental consequences desired. Prescriptions must be based on a sound knowledge of fire behavior as related to weather, fuel, topography, smoke emission, and other factors.

In this chapter, we recognize that several forms of prescribed burning should be identified. Thus, we deal separately with (1) area slash burning, (2) piling and burning, and (3) light underburning.

Area Slash Burning

By far the largest amount of logging slash has been treated by area burning. Often called "broadcast burning," it is used to remove residue from clearcut areas west of the Cascade Range. Occasionally the method is used to burn debris left on some selectively cut areas in the Northwest.

Public fire protection agencies and private protection groups have encouraged area slash burning in west-side Douglas-fir cutovers. In pine areas east of the Cascades where residue amounts are less, the common practice has been to pile the residue by hand or machine in selected locations and burn the concentrated materials.

Slash burning is a carefully planned operation. In area burning on the west side, the practice is to build a fireline by bulldozer around the perimeter to confine burning to the prescribed area. On areas too steep for a tractor, the line is built by hand. Snags close to this line are felled to lessen danger of fire escapes. Other burning safeguards used include sprinkler systems on critical perimeter locations where water can be applied, often several hours in advance of burning. Prelocated pumps and hose systems, ground tankers, and reserve firefighting crews may be used. Retardant spraying on outside areas and other precautions may also be taken. Fireline construction and snag felling are often completed soon after the logging.

Burning is usually done in the fall. In recent years, an increasing amount is scheduled for spring, when conditions for burning fill the prescribed conditions. Some burning along the coast is done throughout the summer. In most areas, there are limited periods when weather conditions are good for burning and when air quality requirements can be met. Concern over pollution by smoke in recent years has greatly reduced the times when effective burning can be done, and further reductions are likely. A smoke management program in Oregon and Washington, worked out by the protection agencies with environmental quality authorities, is being applied with generally good success.

Preparation measures have been intensified to extend burning into portions of the fire season previously considered too critical for prescribed burning. In such periods, the burned areas must be completely mopped up to prevent "escape" fires. These measures may increase the total cost of treatment but are necessary if the'burning is to be completed safely. Because of the many constraints on burning, an agency or an owner will often not get all burning accomplished in the year planned. A modification of the area burning system is often used in which only log landings or concentrations of greatest residue or "jackpots" are burned.

Selection cuttings usually get special measures. Slash-may be hand piled in the larger openings for burning. Concentrations of debris may be pulled away from the bases of crop trees or crushed by special machines. Some area burning is done, mostly along roads or in other limited locations. Here, the purpose may be to remove fire hazard or to prepare a firebreak or fuel break as a place to stop a spreading wildfire. Roads as well as prepared lines are used as boundaries for this burning. Sometimes existing skidding trails are connected and improved as firebreaks. A fireline made by chemical retardants has been considered a good means of controlling or demarking fires in these areas but its use has been limited.

Piling and Burning

Concentrating residues for burning has long been the practice in pine areas but is increasing in Douglas-fir forests. A few private owners and the Bureau of Indian Affairs 20 years ago piled and burned their entire pine residues. There is apparently less of this now, although it is the goal of the Bureau of Indian Affairs, U.S. Department of the Interior. Disposal of residue in mixed conifer forests east of the Cascade Crest calls for a variety of treatments. In some cases the slash is bunched in piles, and in others it is windrowed by bulldozer into more or less regularly arranged rows. Special "brush" blades with teeth are fitted to the dozers to keep soil from getting into the piles; soil in piles makes burning and good cleanup of piles a greater problem as well as adding to the risks of holdover fires and chance of escape.

Large materials, such as logs and chunks, cannot be hand piled, and machines must be used. Often the large material is skidded into piles on which the smaller material may be placed. Both hand and machine piles are often kept dry with waterproof paper or plastic, permitting burning after snowfall or heavy rain when hazards of burning are less and air pollution problems are not so great. The practice of YUMing which produces very large piles that are frequently burned is discussed below.

An older practice of "swamper" burning was frequently used in cutting areas but now is generally restricted to road clearing operations. It consisted of starting a small fire and adding material, usually green, onto it as cut. A modern version uses the open pit, direct-fed incinerator. There are two versions--the dug pit and the portable bin--both equipped to circulate a stream of air over and onto the combustion area. After petroleum or other burning aid is ignited, the airstream creates a strong recirculation action for more complete combustion. Heat gets intense in such pits and even large chunks of wood are completely consumed rather quickly with little visible air pollution. Emissions from forced-air pit burners have not been fully researched.

Many mechanical methods have been used and are still being developed to get residue into the pit or bin. The material may be pushed in by a bulldozer or hauled and dumped into the pit. Bins or burning chambers can be portable and either towed or pushed. Barges have been used to move pit burners along waterways to burn debris picked up on the sides. Various "cherrypickers" or skidders have been used to concentrate the material for the incinerators. One trailer-mounted bin is equipped to do short skidding as we71 as loading. These methods are effective but expensive. Costs per ton of residue are not available but generally are considered too great for widespread application to logging areas. These devices seem well adapted to roadsides, road rights-of-way, clearings, reservoir sites, and other places where a complete cleanup job is demanded.

Light Underburning

About 2 million acres (809,000 ha) of uncut forest are burned annually in the Southern States under their program of periodic light underburning. Such a practice has been used little in the Pacific Northwest to remove natural debris under the canopy of uncut forest stands, though it has been suggested for ponderosa pine. More attention has been given to the practice in the Northwest in recent years, although tests of light underburning for residue removal are really just starting in this area. Similar effects are being obtained by allowing wildfires to spread under prescribed conditions in wilderness areas--an experimental practice that is likely to increase.

Stump scars indicate light underburning occurred in east-side ponderosa pine forests at irregular intervals before the days of forest fire control. Started by lightning or Indians, these natural periodic underburns may have been instrumental in development and perpetuation of some of our forest types.

Brushfield Conversion

Brush or other undesirable growth can be treated by prescribed burning to prepare the ground for a more desirable form of vegetation. If the material is living and green, it will burn only under weather conditions that require extensive preparation and precautions to prevent fires from burning unplanned areas. Of course, this form of brush removal is not practical unless ultimate use of the treated area will justify the costs. Such areas as sagebrush or snowbrush cover have been crushed or sprayed with herbicide or desiccants in advance of burning. After a proper killing and drying period, such areas burn well. Unwanted brush is sometimes bulldozed into piles for later burning or removal where complete cleanup is desired. Windrowing with a grader or similar machine has also been tried but not widely used. In some situations, removal is not necessary and the brush may be merely treated with herbicide to provide release of desired species.

RESIDUE REMOVAL AND DISPOSAL

Removing large residues from cutovers by YUMing has been practiced since about 1970 in west-side National Forests and even earlier elsewhere. This operation usually follows removal of most of the merchantable material before the logging equipment is moved from the area. Yarding the residue with the merchantable logs may be cheaper, but the excessive debris may get in the way of the logging operation. Thus, most YUMing follows regular yarding. YUM piles at landings burn readily even in wet weather after they have gone through a summer drying period. Such burning is better from an air pollution standpoint, and there is little danger of fires escaping to adjacent timberlands. After YUMing, most of the fine fuels are still on the ground, so the practice does not necessarily lessen fire spread but it makes fireline construction much easier in a cutover. Other advantages of the practice include easier planting, a more esthetic appearance, and conditions more favorable for future cultural work.

Except for many YUM piles that are now burned completely, the practice creates opportunities for salvage. Special products such as pulpwood, fuel wood, cedar products like posts and shakes, and similar items often can be obtained from the piles. Much material can be used once it has been accumulated on a road; for example, YUM piles provide a ready source of fuelwood for individuals.

REARRANGING RESIDUE

If the volume and size are favorable, residue may be rearranged or mechanically treated and left. Such procedures are favored where fire and obstruction might be problems and where the maximum amount of organic material is important for soil protection and nutrients.

In some parts of the United States, rearrangement of logging debris has been widely practiced but has only recently gained major attention in the Northwest. Reducing residue with a mechanical chipper has been suggested as a method of making residues more sightly and less of a fire hazard. However, chipping has disadvantages. Because of high costs, lack of equipment to handle large-size material, and the great volumes of logging slash, the practice has never expanded greatly except for cleanup in recreation areas and along some roads. The areas in which chipping is practiced look good, but some fire officials believe chips add to the risk of fire starts as they have along railroad rights-of-way, particularly if the chipped material is not widely scattered. In addition, a chip mulch makes demands on available nitrogen, is not a good seed bed, and in excess of 1 inch (2.54 cm) may be a detriment to artificial reforestation.

Other means of breaking up or crushing residue are gaining attention. Some machines use a flail and some a crusher system to "beat" up or break slash and in the process mix much of it with top layers of the soil. These machines are used on slash produced in thinnings and sometimes on residue resulting from final harvest cuts. Once over with a crusher is of some benefit, and two trips over an area usually makes the residue tolerable from a fire hazard standpoint. Crushers or rollers are widely used in lodgepole pine. If used on heavy soils or in very wet conditions, however, they cause damaging soil compaction. In medium volumes of residue and less precipitous topography, these machines are partially effective but they have not proved satisfactory for the large size material common to old-growth Douglas-fir harvest areas.

Complete burying is sometimes used to dispose of residue from road clearings and from other areas to be completely cleaned. Use of this method in most logging areas is not considered feasible. Besides requiring deep soil and no more than gentle slopes, the radical disturbance of the soil is believed to be damaging to soil processes and growth potential.

Residue produced in thinning operations is sometimes treated by lopping and scattering. This method is seldom used when stands are clearcut because of the large amount of residue usually present, though it may be used where slope, soil, or advance reproduction are such that other treatment is precluded. Normally, a maximum length of material that may be left is specified. This method puts more fuel in contact with the ground where it will decay more rapidly while causing less obstruction. On steep slopes or areas subject to erosion, residue is often placed in skid trails or depressions to slow waterflow and catch water-carried soil and debris.

NO RESIDUE TREATMENT

A common practice is to leave the residue after logging and provide supplemental fire protection to compensate for the increased hazard. The amount of such supplemental protection varies widely depending on the degree of hazard, desires or economic concerns of the owner, and to some extent the requirements of the protection agency. The measures taken include increased ground and air detection, closure to use, more men available for patrols and firefighting, quicker transportation,. specially trained firefighters such as helitack men or smokejumpers, and more readily available equipment such as ground and air tankers, bulldozers, and plow units. If a fire escapes in untreated slash under critical weather conditions, however, it can easily become a major conflagration despite supplemental protection.

Logging slash may be left untreated for reasons of environmental benefits actually achieved, because of the expense of providing the needed treatment, because of physical inaccessibility of the site, or because of legally defined environmental requirements.

Environmentally, leaving logging slash untreated may be the least destructive practice and may actually provide benefits in some situations. However, its potential benefits to soil, advance reproduction, and wildlife habitat are often offset by intolerable fire hazard, persisting obstruction to regeneration and management activities and missed opportunities to remove competing vegetation and influence species composition of the regenerating forest. Wherever no treatment of residue is the alternative prescribed, important problems of protection, regeneration, and possibly others must be solved in advance by other provisions of the timber management operation. These might include road and harvest-area layout with fuel breaks, harvest techniques such as felling and bucking rules to reduce breakage and waste minimum wood, and skidding or yarding requirements to remove the maximum amount of wood. The environmental requirements of soil and watershed protection and regeneration of a new forest would **also** have to be met. Where no treatment of slash is selected because of either inaccessibility or inability of the environment to withstand any treatment, a critical look is needed at requirements for forest regeneration and protection. Without these the land, in effect, is taken out of production. Where provisions assuring establishment and protection of a new crop will not be met, there is a strong implication that harvest should be postponed until techniques are developed that are sufficiently compatible with continued forest production.

EFFECTS OF FOREST RESIDUES AND RESIDUE TREATMENTS ON THE FOREST ENVIRONMENT AND ITS MANAGEMENT-- A HIGHLIGHT SUMMARY

Forest residue management becomes an integral part of the management of the various resources and influences that comprise the forest environment. The 18 technical papers of this Compendium discuss thoroughly what is known about the environmental effects of forest residues and their treatments. Here we present abbreviated highlights of these effects as they influence forest management activities. Only environmental influences are considered; economic aspects are not discussed.

FOREST PROTECTION

Fire Prevention and Control

The presence of dead residue in amount and distribution that precludes effective protect on from fire constitutes the greatest threat to forests and their management. This situation occurs primarily in the form of slash from the clearcut logg ng of old-growth timber, which often leaves 50 to 100 or more tons of flammable debris per acre (112 to 224 metric tons/ha). Fuel of this magnitude, especially in high risk areas, constitutes a critical protection problem.

Special treatment may be justified to lessen this fire hazard. The risk of fires starting from lightning cannot yet be controlled although some evidence suggests that weather modification may be partially successful. Greater access to the forest and increased use continues to make man-caused fires more likely. The most effective residue treatment to reduce the danger of fires starting and spreading is to remove the fine fuels; that is, those pieces under 3 inches (7.6 cm) in diameter. This can be done effectively by some form of area burning. Yarding unmerchantable material after logging will , by removing large material , greatly reduce the difficulty of control of fire but ordinarily will not remove the likelihood of fires starting and spreading rapidly. Piling or bunching and burning fine and coarse debris is an effective fire prevention method. Chipping of residue, especially along roads, will increase man-caused fires but reduce rate of spread and difficulty of control of fires that do start.

Natural residues also occur or accumulate in proportions that are serious fire hazards. Dead residues created by wildfire, insect epidemics, or disease-dead standing trees or snags by providing aerial sources of windblown embers, constitute a threat of burns and reburns as long as they remain standing. Cutting is the usual treatment. The living forest itself produces problem quantities of residue from shed branches to the individual trees that succumb from various causes and competing understory growth. Excess residue can be removed or prevented from accumulating where periodic light ground fires can be used. Under rigid specifications to prevent excessive damage to the stand, this periodic light underburning simulates the natural fires that old fire scars indicate occurred in such forests as ponderosa pine and giant sequoia.

Various residue situations require various treatments. The most effective long-range approach to the residue-related fire problem is a program of fuels management introduced into al1 forestry plans and operations.plus greatly improved wood utilization activities.

Protection from Insects

Undisposed residue attracts many varieties of insects that hasten its decomposition. Few of these constitute a hazard to the forest. However, some serious epidemics of bark beetles have been generated by blown down, fire damaged, or mechanically injured trees that became infection centers. Residues from partial cutting in ponderosa pine can induce insect damage to residual trees, especially those injured by logging or weakened by drought. If the amount of residue is relatively small and the beetle population large, insects may readily spread to living trees from the residue. Other insects associated with residue can cause damage to spruce, hemlock, cedar, and other species under special conditions as, for example, following blowdown. Preventive action would be in the form of removal or modification to a condition less attractive to the damaging insects.

Protection from Diseases

Generally, disease problems are not greatly affected by residue or residue treatment. But some effects have been noted that should not be aggravated. Larger buried residue and, of course, stumps and roots tend to perpetuate the presence of root disease inoculum in the forest. Any mechanical injury to the roots or stems of residual trees by residue treatments may lead to decay problems. Other decay organisms effectively hasten the reduction of residue in many situations. Decay is slowed by waterlogging but is generally faster where temperatures are high and soils are moist. Decay rate is impeded by burning as charred wood seems to be decay resistant. However, fires tend to stimulate the development of the fungus *Rhizini undulata* that has killed conifer seedlings in some Pacific Northwest forests.

Protection from Mammals and Birds

Residue has varied influence on wildlife. In general, living and dead residues improve the habitat for birds and small animals. Following buildups in populations of small animals, most residue treatment, by increasing exposure, will lead to damage of seed and seedlings by rodents and birds. Fine debris tends to deter birds from foraging for seed. Brush piles increase the potential for damage to seedlings by brush rabbits and snowshoe hares. Untreated logging slash often protects seedlings from browsing by big game animals. Browsing by deer and elk, for example, is much greater on burned than on unburned cutovers.

REGENERATION AND STAND DEVELOPMENT

Stand Establishment

Any form of residue removal that disturbs the surface and exposes mineral soil aids germination of seeds spread naturally or artificially. Some residue left to provide dead shade-benefits establishment of natural or planted seedlings, especially on dry, hot sites. Moderate amounts of untreated residue favor ponderosa pine reproduction on many sites east of the Cascade summit. Reduction of heavy volumes of dead or living residues favors seral coniferous species.

Reproduction problems may be associated with residues. Heavy, volumes of chipped or other fine residues form a physical barrier to seed germination and also tie up available nitrogen to the detriment of seedling establishment. Reclamation of heavy brushfields by mechanical type conversion methods may leave up to 40 tons of residue per acre (90 metric tons/ha) to be disposed of before regeneration can be successful. Where residue burning produces intense fires, soil productivity in the area immediately involved may be damaged, seedling establishment may be inhibited, and growth potential may be reduced. Any residue treatment that destroys advance regeneration may retard stand establishment, but regeneration infected with insects or mistletoe may have to be destroyed as a sanitation measure. Generally, residue reduction treatments improve accessibility for tree planting crews while increasing exposure of seedlings to heat, drought, and animal damage.

Stand Development

Conditions favorable to tree growth are enhanced if residues are left on the site to decay and release nutrients, though most critical nutrient is stored in the foliage and little in wood. Especially fine residues afford soil protection, enhance infiltration of moisture, reduce evaporation, and maintain a vigorous soil microbiological activity--all factors that benefit tree growth. Living residues such as unmerchantable alders, maple, oak, or brush compete with more desirable species, occupy growing space, and reduce yields but sometimes serve as nurse crops for young conifers. Residue treatments that compact the soil will result in reduced growth of trees on or close to compacted areas for extended periods, often as long as a rotation. Treatments that result in depletion of the soil also tend to reduce forest growth.

sort. AND WATER

Soil Conditions

Effects of burning vary with the fire intensity, but all burning to reduce residues leads to some loss of nitrogen, boron, sulfur, and phosphorus from the site. Availability of other nutrients will be temporarily increased. Burning tends to decrease wettability of soils usually in proportion to intensity of the burn. Hot fires reduce infiltration capacity of the soil. Microbial activity in the important upper soil layers is impaired by-compaction, encrustation on soil surface, and hot fires. Burns that remove the duff cover from clearcut slopes over 60 percent may cause dry ravel erosion during the summer until vegetation is established.

The largest proportions of the essential elements are contained in foliage. Thus, nutrient return to the forest floor is largely through litter fall. Destruction of living residue will temporarily interrupt nutrient cycling which will resume as new vegetation becomes established on the treated area. Also, the destruction of surface organic layers will have a significant impact on nutrient capital and availability. Treatments that destroy root systems on steep slopes may lead to loss of thin soils. Residue treatment would not normally increase mass soil movement unless heavy equipment undercut sensitive slopes or over-loaded them with debris. If heavy ground equipment is used to handle residues when soils are wet, serious soil compaction will usually result, greatly reducing infiltration and aeration and seriously reducing soil productivity for many years. But residue treatments that incorporate rotted wood, leaves, and crushed or chipped material into the soil will improve aeration, infiltration, and moisture retention properties while causing a temporary nitrogen deficit.

Water Quantity and Quality

Water yields are not usually affected to a significant degree by proper residue treatments, but some influences may be important in certain situations. The destruction of dense living residue would increase ground water temporarily by the amount of transpiration eliminated. Residue treatments that channel water or reduce infiltration rates to speed surface runoff can affect the timing of peak flows in streams. The burning of residues is likely to release large quantities of chemical ions that are lost from the surface soil and may reach streams and impair water quality. Severe burns that remove all organic soil cover can increase susceptibility to surface erosion for 1 or 2 years until vegetation returns. If fine residues get into streams, biochemical oxygen demand will increase and influence stream biology. Removal of living streamside brush may result in increased water temperatures. Any treatment that drastically disturbs the litter and surface soil may lead to surface erosion and stream sedimentation, but this may be somewhat counteracted by leaving some logging slash to protect against erosion. Residue that gets into stream channels may change- stream behavior and result in bank cutting and sedimentation problems or trigger flush-outs of debris dams in steep-walled channels.

FISH AND WILDLIFE

Fish Habitat

The residue conditions and treatments that affect water quality also affect fish habitat. In addition, removal of natural or man-caused residue from streams if done improperly can affect stream hydraulics and bed and bank stability to the detriment of fish habitat. Shade provided by living and dead residue may be essential to maintaining desirable water temperatures and food supplies necessary for fish production. Fine residues in streams affect fish habitat by reducing dissolved oxygen levels in surface water and by interfering with the circulation of intragravel water in spawning beds. Burning of heavy slash concentrations near stream channels can produce chemical and physical changes that will be toxic to fish. Large residues left in streams can interfere with movements of migrating fish, though occasional strategically placed logs will create pools.

Wildlife Habitat

Large volumes of debris depress forage production--the greatest single effect of nonliving residues on game habitat. Most residue treatments that alter but do not eliminate either living or dead residues ultimately enhance the habitat, especially for large animals. Uniform distribution of logging residues restricts the use of cutover areas by elk and deer more than a patchy distribution. Area burning of logging residue improves forage production for elk in most forest types. Living residues mostly favor increases in populations of seed and seedling foragers by providing good food and cover. Burrowing rodents may be attracted to areas where residues are buried. Nonliving residues provide some food but chiefly cover for most animals. Logging slash provides escape cover for small mammals and birds vulnerable to predation by hawks, owls, weasels, and coyotes.

RECREATION AND ESTHETICS

Residue and residue treatments strongly affect landscape amenity. Practices that preserve naturalness, harmony in shapes, horizontal and vertical order, uniformity in texture of the forest, and avoid the appearance of waste may each or in combination contribute to esthetic values. Undisturbed residue in precommercially thinned stands is esthetically undesirable. Crushing small amounts of logging slash improves the appearance of the treated area. Reduction of debris usually improves access by fishermen and hunters.

DOMESTIC LIVESTOCK GRAZING

Untreated residues often hinder the movement and grazing of livestock more than wild grazing animals. Patchy residues are less of a detriment than those that are continuous and uniform. Residue treatments, such as burning, may have a beneficial or harmful effect on plant succession and grazing values dependinq on the vegetative type and the burning prescription. Practices that cover the soil with organic material,-as in chipping, suffocate small shrubs and herbaceous plants that livestock might eat.

AIR QUALITY

Residues have no significant effect on air pollution although as they decay they contribute carbon dioxide, methane and other hydrocarbons, and ammonia to the atmosphere. Residue reduction by fire is the only treatment that significantly affects air quality. However, the heavy volumes of logging slash and accumulation of dead fuels through years of intensive fire protection can lead to wildfires that result in more serious air pollution incidents than a program of prescribed burning with smoke management.

Residue fires produce emissions that vary widely with fuel characteristics, arrangement, condition, weather, and other factors. Emissions can be minimized by planning a burn to produce the hottest fire and minimum smoldering time. Area slash burning produces more smoke per unit of fuel than pile burning, assuming open, soil-free piles. Head fires produce more smoke than backing fires. Dry fuels produce less smoke than damp; and flaming fire, much less smoke than smoldering. Controlling the time, place, and method of burning to take advantage of favorable dispersion weather can go a long way toward protecting populated areas from smoke. Prescribed fires should be planned and scheduled to burn under conditions that will produce a strong convective column and smoke dispersal away from valley areas or other smoke-sensitive situations.

There is little evidence that combustion of forest fuels produces emissions that are permanently injurious to human health. In some situations, the smoke from residue burning can temporarily reduce visibility and affect esthetics.

SOLVING RESIDUE PROBLEMS

Man is an important part of every forest environment. As long as he chooses to use the forest there is no way he can avoid recognizing residues as an obstacle to some of his activities and therefore a problem. But residues also serve important functions in the forest environment and, hence, can benefit the forest and the goods and services it provides. Therefore, residue management programs must be developed with consideration of all the beneficial as well as detrimental factors and circumstances. In this section we shall discuss what can be done to help resource managers deal with residue problems.

ESTABLISHING RESIDUE MANAGEMENT GOALS AND POLICIES

The management of forest residues is closely tied to management of the forest environment, which is made up of a number of different components--soil, water, air, plants, animals, scenery, insects, diseases, and fire. Ideally, management objectives need to be set for each component. But forest situations vary in time and from place to place. Certain environmental components may dominate one forest and different components another. This may be due to differences either in environmental conditions or in land use objectives. The goal for each component stated separately may be a condition that only occasionally may be fully achieved. It should always be approached as closely as possible with minimum violation of the goals for other components. Thus, the resource manager needs to be able to select the residue management alternative that comes closest to satisfying all his environmental goals without causing unacceptable impacts on any one of the environmental components. When this is not possible, his composite goal may have to be based on avoiding any long lasting negative impact. For successful and consistent residue management, the resource management agency must have carefully defined goals for each environmental component plus guiding policies and procedures for determining the best composite course under any combination of environmental conditions and forest management objectives.

EXAMINING ALTERNATIVES

Every residue situation and every measure used to deal with a residue problem have associated benefits and costs.[4/] But what may be a benefit to or an aid in achieving one management goal may be a cost to another. For example, logging residues cannot be burned without some effect on air quality. But the costs associated with not burning may be in the form of increased risk of costly accidental fires and a potential loss of adjacent timber, and an even more serious impact on air quality.

Different resource management goals require that different policies and programs be followed, each with its own set of impacts or costs. If the goal is to maximize anadromous fish production in coastal streams, a policy might be established to prevent any activity that would allow residue or residue treatments to change water quality beyond specified limits. Such a policy might then require that protective buffer strips of trees be left along streams to maintain favorable water temperatures, that sediment be minimized in spawning areas, and that chemical degradation of water by residue be kept below specified levels. However, if the goal is to maximize big game production, perhaps none of these constraints on residue management would be applicable. Others would take their place.

The forest manager is continually faced with choosing among courses of action and program commitments based on the impacts of each on the environment and on his budget. Residue management not only has immediate and long-term effects on vegetation, soil, water, air, and their uses by man but each management decision usually requires a different investment when available dollars are limited.

What criteria, then, should a manager use to identify alternatives and evaluate their implications? To start with, he can usually determine the direct cost of a residue treatment. He may know, for example, that a single aerial application of an herbicide to kill a stand of worthless brush may cost $20 per acre. Or he knows that YUMing in a given situation may cost $400 per acre. But what does he "buy" with these investments?

In some instances, especially if a commercial timber crop is involved, the manager can evaluate a treatment in terms of present worth of a future expected income. For example, it would not be difficult to calculate the dollar benefits associated with, say, area slash burning that hastened by 10 years the full stocking on an area freed of heavy brush competion with a $75 per acre burn ($185.25/ha). Perhaps two $20 aerial herbicide sprayings spaced 3 years apart

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4/ "Costs" as used here include all the negative requirements and effects of a residue management program measurable in dollars or in unquantifiable terms.

would shorten the regeneration period by 5 years. The difference in timber production between the two treatments could be calculated. Dollar costs of this kind are compelling considerations and are usually available to a manager. This Compendium of papers concentrates on environmental factors only and barely hints at such costs.

Unfortunately, the most critical decisions a residue manager must make involve comparisons of impacts that cannot be evaluated in dollars. What, then, does he do? A partial answer lies first in identifying and comparing the desirable and undesirable effects of a given residue treatment. If the undesirable impacts of one possible choice are unacceptable, another course of action can be considered and its impacts identified.

The 18 papers in this Compendium describe what we know about the biological, physical, and socially oriented impacts of every aspect of forest residue and residue management. These impacts must all be considered and evaluated by the manager in the course of defining his goals, policies, and programs. Some examples may illustrate how the impacts can be arrayed and compared for a specific residue treatment. In these examples, we recognize that the generalized desirable and undesirable impacts we have listed may not apply to every situation. Managers must understand and adjust for such variations in impact factors by using the detailed background discussions to guide their judgments.

Example 1: Environmental impacts of chipping residues (not listed in order of priority)

Desirable impacts:

1. Lowers rate of spread of fire and eases difficulty of control.
2. Reduces soil movement and danger of stream sedimentation.
3. Keeps nutrients on site.
4. Maintains or improves desirable soil microbiological activity if chips are well dispersed.
5. Lessens evaporation of moisture from soil.
6. Hastens decomposition of residue.
7. Reduces insect problems in some situations.
8. Improves access to area for subsequent activities.
9. Is esthetically acceptable.
10. Does not degrade air quality.

Undesirable impacts:

1. May increase fire risk along roads and other high-use areas.

2. Heavy equipment used may compact the soil in some situations, reducing site productivity.

3. Reduces dissolved oxygen and damages fish habitat if chips get into streams.

4. Interferes with natural reseeding of most desirable tree reproduction.

5. Hinders efficient tree planting.

6. Reduces nitrogen available to regeneration unless accompanied by fertilization.

7 Smothers herbaceous plants and grasses used by livestock and seedlings growing on slopes.

8. Increases vulnerability of reproduction to big game animals and livestock.

Example 2: Environmental impacts of prescribed area slash burning of logging residue (not listed in order of priority)

Desirable impacts :

1. Greatly reduces fire risk, rate of spread, and difficulty of control.

2. Increases availability of most mineral elements.

3. Increases the amount of mineral soil seed bed needed by most desirable species.

4. Reduces competition of brush with regeneration.

5. Removes diseased advance reproduction where present.

6. Removes threat to new stand posed by insect-infected advance regeneration in some types.

7. Favors better tree form in saplings.

8. Provides easy access for regeneration and cultural operations.

9. Improves browse and forage for big game animals and livestock in many situations.

10. Improves access to recreationists, hunters, and fishermen.

Undesirable impacts:

1. Often kills marginal timber, and "escape" fires can further damage neighboring resources.

2. Intense fires can cause soil erosion on immature soils, lessening site productivity and leading to sedimentation of streams.

3. Lowers site quality in areas of extremely hot burns.

4. Lowers infiltration capacity by creating a "nonwettable" condition on some soils.

5. Results in short-term losses of nitrogen and phosphorus which may be of special significance on low- or medium-quality sites.

6. Temporarily interrupts nutrient cycling.

7. Sets the stage for a flush of mineral nutrients into nearby streams where they may damage aquatic habitats.

8. Destroys tree seed and desirable advance regeneration.

9. Increases vulnerability of tree seeds to birds and of seedlings to browsing by big game and livestock.

10. On steep slopes may trigger downslope movement of soil, gravel, or debris that will bury or uproot seedlings.

11. Creates less favorable microclimate for seedlings, especially on adverse sites.

12. Puts smoke into the air.

13. Is esthetically unattractive for several years.

Example 3: Environmental impacts of yarding unutilized material (YUM) after clearcutting (not listed in order of priority)

Desirable impacts:

1. Greatly reduces difficulty to control fires.

2. Aerial system of removal leaves fine residues in place and maintains organic cover, thus providing for protection against erosion.

3. Keeps major amount of nutrients on site.

4. Maintains soil microbiological activity.

5. Lessens probable damage to reproduction by rodents.

6. Stimulates more complete residue utilization for wood products.

7. Improves access for reforestation and subsequent cultural operations.

8. Improves production of and accessibility to forage for grazing animals.

9. Improves access for recreationists, hunters, and fishermen.

10. Is esthetically acceptable.

11. Provides flexibility to burn (the YUM pile) when air quality can best be maintained.

Undesirable impacts:

1. Usually does not reduce danger of fires starting and spreading.

2. Can lead to soil compaction and reduced tree growth if ground equipment is used when soils are wet.

3. Intense heat may damage soil excessively if residue piles are burned.

4. Creates less favorable microclimate for seedlings, especially on adverse sites.

5. Is not effective for control of brush competition after logging.

6. Increases vulnerability of seedlings to browsing by animals.

Example 4: Environmental impacts of chemically treating living residues (not listed in order of priority)

Desirable impacts:

1. Adds to dead fuel volumes and aids spread of fires in prescribed area-burning.

2. Is the most effective method for killing most sprouting brush species.

3. Can-be used on steep slopes where mechanical equipment cannot operate or where soil compaction would result.

4. Creates an acceptable balance between rodent populations and regeneration.

5. Reduces competition from unwanted vegetation for moisture, nutrients, light, and space, thereby aiding establishment of desired species.

Undesirable impacts:

1. Increases flammability, adding to fire control problems unless accompanied by burning.

2. Herbicides used may get into streams and upset aquatic biology.

3. Interrupts nutrient cycling.

4. Releases chemical resistant plants to grow more vigorously.

5. Short-term results are not esthetically pleasing, especially near urban and recreational centers.

MAKING THE DECISION

Once the desirable and undesirable impacts of alternative residue treatments have been identified as illustrated by the above examples, the manager must determine which trade offs are most acceptable when all variables are considered. He will realize that environmental impacts vary with site, topography, geography, resource values, and other factors. For example, an unsightly residue situation does not impinge negatively on esthetic values if no one now or in the future is likely to see it. Improvement of forage due to residue treatment is not a benefit if game or livestock are not present to utilize it. A modest loss of soil nutrients may be of great concern on an adverse site but of mi-nor consequence on a site rich in nutrients. A manager must understand and adjust for such variations in impact factors. The detailed papers of this Compendium may be used to guide his judgment. His decision will also be influenced by the funds he has available and competitive demands on these funds.

On the basis of the contrasting impacts shown in the examples, a residue manager might conclude that he would use the chipping method (example 1) along a heavily used recreation road where esthetic values were high, where burning was not feasible, and where fire patrol was frequent. He might avoid use of chipping in areas where soils compacted easily, where soil protection by organic material was not needed, and, of course, when cheaper methods were feasible.

Area slash burning has many desirable impacts as example 2 indicates. A residue manager probably would seek another method of treatment, however, if he had an area covered by well-spaced advance regeneration, a high deer population likely to browse newly planted seedlings, and a nearby population center sensitive to smoke in the air.

Yarding unutilized material (example 3), often a costly residue treatment, might be most useful in areas where future ground access was highly important, grazing values were high, general removal of litter and vegetation was not desired, and disposal of residue by burning was restricted to fall and winter seasons. In a location where numerous operators were interested in utilizing residue for energy or products, YUM might be favored.

Thus, for each situation, a thorough consideration of alternatives and the costs and benefits will guide the judgment of the residue manager. Someday we may have sufficient knowledge about environmental impacts and operational costs to provide the manager with a model by which he can maximize the net benefits among a range of treatment alternatives. Right now, a thorough knowledge of impacts as set forth in this Compendium will be a useful substitute.

INTEGRATING RESIDUE CONSIDERATIONS WITH MANAGEMENT ACTIVITIES

Residue is something like a forest fire. If it can be prevented there is no problem. The prevention approach may seem like proposing utopian conditions as a cure, but much can be done to make this statement true. When future forests are harvested, residue should be much less of a problem. Forests will be better managed to use much of what now ends up as residue. As the forests grow, cultural measures will prevent unusuable material from accumulating. Frequent thinnings can be made to capture mortality for use in cellulose products. Today's overmature old-growth forests of the Northwest are often decadent and produce much unusable residue. Future commercial forests, grown on shorter rotations, will have little chance to deteriorate; and improved utilization opportunities will keep harvest related residues within tolerable limits.

Weed plants and trees have been allowed to grow promiscuously in most current stands. In the future, crop trees will be planted and thinned to a spacing that will fully utilize the site for greatest tree growth. Little space will be left for unusable material. Improvements in current practices can produce many such results.

Better protection of forests means less residue. There will be less residue if there is less mortality from fire, insects, disease, and weather extremes.

Stability of land use will reduce the residue problem. Changes in land use--for example, from forest to agriculture--produce residue problems. With roads, utilities, and similar uses in a common corridor there is less residue. In an ideally managed forest of the future, we can expect roads on permanent locations, utilities probably underground, or some air transmission system will be common. Other service facilities will be shifted less frequently. Stabilizing land use produces many other advantages, as well as lessening residue problems.

Much can be done in timber harvesting to reduce residue volumes. Subsidizing removal and use of wood residue concurrently may be more economical in a total management program than to take only the better material and leave much residue with its attendant problems. In a government timber sale, an operator might be allowed a lower stumpage price to remove lower grade material rather than require him to pile and burn or otherwise dispose of a large volume of logging slash. Improvement of practices associated with YUM should be developed. Integrated operations especially keyed to the assembling, sorting, and processing of residue should be stimulated. Incentive programs to get this type of harvesting established should be explored. Such programs are in effect in some places now and point to new approaches to residue management via contractual provision. The result can be economically favorable while providing esthetic and other environmental benefits.

A recent study concluded that the use of residue for power production was not economically feasible at 1973 prices and in competition with conventional power. However, it might be better for society to subsidize such use for the general overall good. There are several ways to do this, such as through sharing in capital plant investment through a nonrepayable grant, special provisions for accelerated depreciation for income tax purposes, and indirectly through a general price increase for electric power from all sources.

Finally, we believe it essential that each forest manager view the residue problem as an integral, not separate, part of his total resource management program. He should constantly ask himself such questions as: Can I avoid debris problems in streams if I prescribe a different timber falling method? How can I locate this road network to enhance residue utilization and still serve other resource management needs? What cutting unit layout will lead to the most economical operation and the greatest utilization of marginal logs? If I do not burn this slash area, will I seriously reduce browse available to big game?

The development and use of every resource touch on residue management. Consideration of the residue problem should enter into all planning and managment activities from the beginning. Only throuah close integration of activities can we get to the soundest treatment of each residue situation.

A PROGRAM FOR DEVELOPING POLICIES AND GUIDELINES[5/]

A recent concerted effort to formulate residue management guidelines is worth reporting here to illustrate one approach for utilizing the mass of technical information as guidance for resource management decisionmaking. Region Six and the Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, recently convened panels of scientists and managers to prepare technically sound guidelines that were administratively attainable.

Top research scientists and administrative staff specialists familiar with Northwest resource conditions were formed into nine technical panels covering the following environmental components: (1) forest soils, (2) silviculture, (3) terrestrial habitat, (4) fire management, (5) forest insects, (6) forest diseases, (7) water quality and aquatic habitat, (8) air quality, and (9) forest recreation. These technical experts were provided three requirements for the guidelines they were to formulate. First, guidelines had to be based on the best available scientific information. Second, guidelines applicable only to a particular geographic region had to be restricted to that region within the guideline itself. And finally, no conflict among guidelines would be tolerated. Any conflicts arising during formulation were to be resolved, if possible, by requiring different methods of performing residue treatment for different situations. If this could not be worked out, then an administrative decision favoring a selected environmental component would be made.

The requirement for scientific soundness was to be accomplished by using the information in the 18 Compendium manuscripts and through the knowledge and experience of the panel members. Their job was aided by prepared citations of specific residue and treatment effects assembled from the manuscripts. The citations were used as the basis for computerized cross referencing and retrieval, documentation for the resulting guidelines. Panel members were also encouraged to draw upon and document additional pertinent references.

Each panel produced a set of statements, backed by citable authority, specifying the degree of residue removal and limitations on treatment method required for acceptable management of the particular environmental component. When the requirement varied for different residues or geographic areas, the necessary restriction or specific exclusion formed .part of the statement. The statements prepared by the technical panels were carefully examined to identify conflicts either within or between environmental components. The chairman of the nine technical panels then had the job of resolving technological conflicts.

After the technical conflicts were resolved, two panels of experienced forest administrators were used to reconc'ile technical desirability with economic and social considerations. One panel adopted the statements for use as guidelines to be applied to public lands; and the other panel those to be applied to private lands. Hence, the guidelines are different for private and public lands and take into account the complexities and variations among forest types,' soils, climate, geography, and management objectives.

5/ The publication listing the guidelines and presenting details for their use is being prepared by the Forest Residues Reduction Program of the Pacific Northwest Forest and Range Experiment Station.

The guidelines to be used as tools to aid resource managers confronted with residue problems, can be arranged in various formats. One will consist of a dichotomous key. The manager can proceed through the key to identify the action he should take for any specific residue situation by vegetation type, geographic area, or other variable with which he may be particularly concerned. Extensive testing and evaluation may be necessary before the value of this approach can be confirmed.

These initial guidelines could signal a very important forward step in environmental management. With a firm foundation in scientific fact and with response to social and economic realities, the guidelines may ultimately lead to recommended changes in laws, regulations, and policies. Based on the best that is currently known of the way the forest environment operates, these guidelines may be considered ***interim*** because of the expectation they will be revised as new knowledge is attained.

FUTURE NEEDS

Much needs to be learned about residue management before we can be fully satisfied with the information base from which policies and programs are developed. But policies and programs are not based on facts alone. A whole series of important organizational, administrative, and political necessities are ingredients in the formation of any policy and the major programs for implementing it. For example, if one were to conclude that wood residue had to be used to alleviate an energy crisis because of domestic problems and international situations, he might find little value in studying how to broadcast burn residue more efficiently.

The point here is that new knowledge influences policy and programs, but the selection of research priorities within the constraints of limited research resources cannot be made wisely without some attention to policy. It is with this philosophy that we attempt to identify the principal, residue management research needs.

We have adopted some broad assumptions of resource use trends and policy changes as a basis for judging the problems that should be emphasized in research. The main assumptions include: (1) A continuing upward demand for wood fiber will make greater removal of residues for productive use economical and place increasing importance on maximum production from commercial forest land. (2) A continuing increase in both the demand for nontimber resources and in the concern for environmental values will require residue treatments with greatly reduced negative impacts on the environment. (3) Resource conflicts brought about by residue problems will increase the cost of forest management substantially and will bring growing pressure on the administrator to improve residue management. These point to a steadily increasing intensity of resource management based on expanding knowledge--the product of research.

HIGH PRIORITY RESEARCH

Each author who prepared a section of this Compendium on residues and residue management has described the research needed to solve problems as he viewed them.

Altogether, these research suggestions make a tremendous list--we have tried to identify the principal problem areas in residue management and the research necessary to achieve and maintain an acceptable forest environment in a reasonable time. We do not, however, present here a detailed list of studies that need to be undertaken. Four broad categories of needs are discussed briefly in order of priority:

1. Better information on the nontimber resource values--water, forage, recreation and esthetics, fish and wildlife habitat, and air quality--and the effects of residue modification measures upon them.

2. Predictive models for comparing the economic, social, and environmental consequences of and trade offs between alternative residue management systems:

3. Expanded knowledge of impacts of residue treatments on timber production, especially the long-term effects of the principal measures that influence site productivity and net timber yield.

4. Measures that will hasten the degradation of residue onsite.

Effect of Residue Treatments on Nontimber Resources

Scientists have struggled with measuring the impact of residue and its treatment on soil and water, fish and wildlife habitat, and livestock forage for several years. Much of this research has dealt with the effect of residue disposal by fire. As environmental concerns have grown, the need for better information on the nontimber resource problems has risen rapidly. Managers must now make operational decisions with full consideration of impacts on resources that earlier were of limited direct concern. Air pollution, esthetics, and recreation are examples of resources that only a few years ago were not considered by managers in many situations.

Of the research performed on nontimber resource problems, we probably have the best information on impacts of fire on soil and water. But even this is inadequate today when water quality values loom so large. Particularly as new residue management methods are developed and applied, such as YUM followed by burning, we must evaluate their impacts on soil and water resources.

Quite often in the rainy Northwest, soils are wet during much of the logging season. The use of heavy machines to skid, bunch, crush, chip, or otherwise treat residue can lead to long lasting soil damage, erosion, and reduced future timber yields. We need to know under what conditions and on what soils environmental damage can be minimized if heavy machines are necessary in a particular operation.

We are especially deficient in our knowledge of the esthetic aspects of residue problems. We need to learn how to identify the way people assign landscape values and how they are affected by changes, such as residue treatment. We must determine the relative importance of conflicting elements in the landscape.

Work on fish habitat must be expanded to enable us to relate accurately the biologically oriented studies (fish biology) with the physically oriented studies (the attributes of a habitat) so that the response of an entire aquatic ecosystem to residue management can be understood.

Research on air pollution from forest residue burning is in its infancy. Much more needs to be learned about the components of forest fire smoke, the atmospheric processes in which these components are involved, and the actual toxicity of compounds in smoke. Better methods should be developed to guide the field forester to judge from variables such as fuel composition, fuel condition, atmospheric factors, topography, and location: (1) how much smoke from residue burning will be produced, (2) how' smoke will be dispersed, and (3) what changes in air quality may be anticipated downwind.

Evaluation of Trade Offs

A residue manager is constantly faced with decisions involving trade offs. He has limited funds and must choose the treatment that will buy the most in achievement of residue programs and avoidance of undesirable environmental impacts. This job would be difficult even if we had abundant biological and physical information on every environmental consequence of every residue treatment. But when one adds the problem of quantifying hard-to-evaluate impacts, the task is especially challenging.

Help can be made available through research in the field of modeling in which the best data and experienced opinions are put together into a matrix that will provide a treatment "answer" to each type of residue-environment situation. Many residue and treatment impacts cannot be expressed in dollars. Some impacts can best be described in terms of the *likelihood* that specific conditions or sequences of events will result from a particular residue treatment. Models presenting the probability of consequences for each treatment will be most helpful to an administrator. Research into the development of predictive models is of high priority.

Research on Timber Production

One obvious result of environmental concern is that constraints are being placed on the cheaper and easier methods of timber production. There are compelling reasons for such actions. However, the situation requires that we accelerate research on regenerating and culturing timber crops to meet present and future wood requirements and lessen through improved practices any negative environmental impacts that may once have been accepted as a routine part of the timber production cycle.

As we move away from burning and begin to use other residue disposal methods more and more, many questions about the best regeneration methods arise. In most forest types that are regularly logged, better information is needed on the establishment, survival, and growth of seedlings. For the millions of acres of productive timber sites occupied by living residue, we need improved conversion methods. Silvicides, herbicides, desiccants, and biological agents that do not contaminate the environment and that are effective on resistant residue species are needed.

Much attention has been focused on residue removal and the nutrient cycle. Some information is available, but for the Northwest we need to understand much better the effect of all residue treatment methods on soil nutrient levels, nutrient cycling, and site productivity for any managed forest.

Dearadation of Residues

In spite of all the promising methods we have for residue removal or modification, large natural accumulations and untreated logging slash will continue to build up as environmental benefits and resource management requirements are accepted as legitimate trade offs to residue disposal. Because of the tremendous fire hazard these untreated residues represent, ways must be found to hasten their deterioration in place. Degradation is, of course, brought about by weather, decay, insects, and soil micro-organisms. We need to learn much more about the role of insects, microbes, and decay organisms in residue decomposition. We should determine whether chemical additives or other treatments can directly stimulate the rate of breakdown by these agents. Although this field of research is complicated and long term, it could have significant payoff.

Other Research

By not mentioning an area of research in the foregoing paragraphs, we do not imply that knowledge is adequate in that area. The individual papers of this Compendium go into further detail, and many of the other studies are of high priority.

EQUIPMENT DEVELOPMENT

The development of machines usually lags significantly behind the need for improved application of a management practice. New machines can be efficiently built by equipment manufacturers providing they know the engineering requirements, understand the biological constraints imposed by the resource, and see a favorable market for their product. Here we suggest the more obvious developments that would aid residue management.

Improved Technology for Residue Handling

With the steadily growing restrictions on area burning of logging slash, numerous alternative measures already described are being used to assemble, remove, or change the form of debris. These measures, adopted from other activities, almost always involve the use of either heavy machinery, that can severely damage the soil, or of specialized logging systems, that are expensive to operate. YUM operations, for example, are primarily carried out by logging systems designed for primary removal of timber. The use of the same system for residue removal is usually costly to the operator and consumer because of its inefficiency with the smaller, more irregular material. Helicopter logging, an extremely expensive system, may prove to be highly desirable from an environmental impact point of view in primary logging, for example, but completely unsuitable for the removal of shattered, rotten material from a prime fish producing stream. However, YUMing by any system not only removes the large material but can lead to more intensive utilization which in itself has an indirect but far-reaching benefit to the environment.

Research is needed to develop new concepts for handling small to large chunks and fragments of unmerchantable wood to put it in the best form for the chosen disposal method. Engineering systems analyses, starting from defined environmental constraints, should be able to produce concepts of systems that would fit each residue management situation. Design, construction, arid evaluation of hardware would follow.

Improved Equipment for Concentrated Burning

Bin burning is likely to increase--especially for disposal of residue, in heavy-use areas, along roads, and near developments such as campgrounds, ski runs, or administrative sites. Better bins or open incinerators with efficient blower systems, made of materials that will resist intense heat, and that can easily be moved are needed. Presently, these burners are not easy to move and bringing slash to them is costly. Similarly, we need to improve machines that will efficiently concentrate, pick up, and move residues to the burner.

Residue Processing

If a technology is developed that will efficiently concentrate residue on a landing at roadside, improved methods are needed for sorting the highly variable sizes and qualities of logs and chunks into product quality classes to enhance the likelihood of their being used. Better systems to debark, sort for highest value use, and preprocess residue at intermediate points between forest and mill are needed. Equipment will be needed to facilitate the disposition of rejects from a residue processing point. Bark, rotten wood, branches, needles, and other unusuable residue must be handled cheaply and neither interfere with residue processing nor result in an additional solid waste problem.

Improvement of Fire Retardants

Establishment of firelines around cutting units to be area burned for residue disposal would be greatly enhanced by the development of a fire retardant that could be used at the time firelines are built, usually before the logging operation is completed. Such use would require that the retardant be capable of persisting for several months. It would thus have to remain effective through perhaps 2 inches (5 cm) of rainfall. A retardant with these capabilities would make unnecessary many bulldozed firelines with their attendant soil damage and esthetic impact.

COORDINATION OF ALL EFFORTS - A FOREST RESIDUES RESEARCH AND DEVELOPMENT PROGRAM

In spite of the substantial knowledge brought together in this Compendium, much more research and development are needed before we can feel confident that a sound basis exists for an effective residues management program. To meet this need, various research organizations have continuing work underway. Several universities have substantial studies aimed at clarifying residue impacts on soil, water, wildlife, regeneration of trees, and other resource values.

The Forest Service, U.S. Department of Agriculture, has identified its programs of study in formal projects. For example, the Intermountain Forest and Range Experiment Station's Missoula, Montana, project has a program directed at determining: (1) What technically, ecologically, and economically viable alternatives exist for reducing the volume of wood left as residue after timber harvesting? (2) What are the esthetic and environmental consequences of alternative timber harvesting and transportation practices, and how can adverse practices be reduced? (3) What opportunities exist for development of new or expanded markets for the currently unused residue?

The Pacific Northwest Forest and Range Experiment Station recognizes the urgency of a residues research program as this Compendium attests. It has suggested an approach that would include research on: (1) procedures for selecting optimum treatment alternatives for residue situations to meet variations in environmental factors, costs, other constraints, and differing management goals; **(2)** materials handling and preprocessing possibilities to make residue utilization feasible and more profitable and to evaluate innovative marketing procedures for timber to encourage better utilization and land management; and (3) improvement of our knowledge of the effects of residue and residue treatment on all resources and. better ways to assemble and index what is known for easy use by the resource manager. The Station also recognizes that trials, tests, and demonstrations of practices and the training of managers in the use of the best residue practices are essential to the success of a broad residue program.

Other Forest Service units are actively contributing to a better understanding of residue problems. For example, the U.S. Forest Products Laboratory at Madison, Wisconsin, is doing research on utilization of residues in modified wood products such as particle boards. Various aspects of smoke production and management from prescribed burning are under study at the Southern Forest Fire Laboratory. No attempt is made here to summarize other research underway.

The complexity of the residue problem makes a total environmental effects, economics, and utilization research program imperative. The overall problem will not be solved by just a water, air, and scenery program; by a soil, plants, and animals program; by a fire, insect, and disease influences program; nor by attention to economic and utilization concerns alone. What is needed is a total program properly coordinated so that the effort available in research, development, and application is efficiently used.

A Forest Residues Research and Development Program, as it might be called, should be carefully planned. The new knowledge and techniques developed by the program need to be directly used in the formation of improved practice guidelines, management policies, and operating programs. Resource managers will then be able to apply the best technical knowledge available to the particular set of environmental and economic considerations encountered in each residue situation.

No simple avenue for achieving a fully coordinated program can be identified. In research, many devices have been tried, including program planning conferences, centralized control of research assignments, stimulation of exchange of knowledge and plans among researchers, use of advisory committees, and similar methods. A strong effort of residue research coordination should be made through some type of centralized planning. Transfer of information between research scientists and the user is essential both from a policymaking and a management point of view. And finally, skillful and well-trained professionals are. needed to interpret and apply knowledge, policies, and programs to fit the residue situation each may encounter. We believe this Compendium provides a starting place for a full-scale and effective forest residues program.

CONCLUSIONS

After reviewing the state-of-knowledge of forest residues, and on the basis of some years of experience dealing with residue-related problems in forest management and in research, we have come to several conclusions:

1. Study of the 18 specialized papers herein reveals that forest residues deserve the attention now being given to them. That there is not full agreement among scientists of different specialties on the effects of residues and their treatments supports the argument that each land area is best regarded as unique. There are also residue conditions and treatments that appear to enhance one resource to the detriment of others. Research is needed to provide guidance to management for these conflicting situations.

2. Forest residues have broad influences on the forest environment, both beneficial and detrimental, as do residue treatments. To achieve the optimum balance for any given combination of management objective-environment-residue situation, planning for residue management must be included in the initial phases of area use planning.

3. Development underway of forest residue management guidelines, based on current knowledge of effects on environmental components, offers an immediate opportunity to strengthen an important aspect of forest management for a high level of environmental quality.

4. Though specifically omitted from this Compendium, certain subjects have a close relation to forest residues and need further research and development. These include:

   a. Handling and utilization of residue.

   b. Economics of residue utilization, treatment alternatives, benefits, and detriments.

   c. Forest harvest methods that produce minimum residue.

   d. Environmental impacts of harvest and transportation systems.

5. Many methods of treating many kinds of residues are discussed. Because of the complex variations in the forest environment and in the demands for products and services placed thereon, no simple set of rules can accomplish environmentally sound forest residue management. Guidelines can be a tremendous help, but flexibility within the limits of technical knowledge is necessary to assure adaptation of management practice to environmental needs.

6. Certain forest residue problems stand out in urgent need of research attention. Many individual high priority studies are discussed in the Compendium.

7. Procedures are needed whereby the forest manager-planner can achieve scientifically sound trade offs between benefits in residue situations

if available treatments do not offer alternatives that are optimum for every environmental component.

8. In these days of ever increasing demands for both a quality and a productive forest environment, we can no longer afford the luxury of assuming that any forest residue problem that may arise can be ignored or taken care of after it becomes critical in visual impact, obstruction to regeneration, intolerable fire hazard, stream and watershed impairment, damage to fish and wildlife habitat, or impacts on other resource values.

9. Our final conclusion is that the great amount of research capsulized in the following papers has been organized to provide a wealth of information to the serious forester with an interest in solving forest residue problems.

SOIL MICROBES

Walter B. Bollen

ABSTRACT

*Interactions between soiZ microbes and forest residues me controlled by six environmental factors:' water, temperature, aeration, pH, food supply, and biological interreZationships. A change in one induces change in others. Burning drastically affects all six but is especially unfavorable in terms of nitrogen Zoss and effects on soiZ physical properties. Microbial decomposition of residues, in contrast, recycles the nitrogen and can result in improved soiZ physical properties. Microbial activity can be enhanced by reducing particle size of residues, by providing good contact between **residue** fragments and soil, and by **adding** nitrogen by fertilization or establishment of plants with nitrogen-fixing nodules. Petroleum products, biocides, or fire retardants appear unlikely to significantly affect soiZ microbial activity or residue decomposition when used at recommended rates. Forest residues combined with soiZ microbes offer promise for disposal of sewage waste water and decomposable garbage.*

Keywords: Soil microbes, residue decomposition, nutrient cycling, chemical interaction.

INTRODUCTION

The forest soil is a basic industry resource and is important in determining sustained yields. Contributions of forest residues to this resource should be so managed that their store of nutrients can be effectively recycled and their desirable physical effects maintained. Availability, storage, and loss of nutrients in forest soils depend largely upon microbial activity. These nutrients are derived from both atmosphere and soil, but especially from the accumulation of organic residues. Forest residue treatments, therefore, will affect nutrient cycling and loss through their effects on either or both the microbes and forest floor, which provides microbial substrates. For example, as will be discussed later, the nitrogen content of slash is lost to the atmosphere by burning; if the slash is left on the ground, much of this nitrogen will be recycled to the soil through decomposition.

The microbiology of forest soil involves complex interactions between a great diversity of organisms and microhabitats. Forest soil varies from site to site, of course, and little is known about it compared with agricultural soils. Nonetheless, many of the fundamental factors affecting soil microbial activity are known and can be expected to apply to forest soils and residue situations.

Decomposition of plant and animal remains is essential to circulation of nutrients in nature, thus constituting a mineralization of organic matter. Soil micro-organisms are active in four major zones of decomposition: surface debris, turned-under residues, humus, and the rhizosphere—a narrow zone around living roots. These zones vary in extent under different conditions, may be adjacent or intermingled in time as well as in space, and vary in intensity. Each zone has peculiar significance and contains a variety of morphologically and physiologically different organisms. Fresh residues support a wide mixture of organisms able to rapidly attack the water-soluble constituents, after which they decline and are replaced by organisms adapted to more resistant substances. As decomposition proceeds to humus, other specialized bacteria that can work on the resistant lignocelluloses and nitrogen complexes take over. If no further organic additions occur, the final product is an accumulation of dead bacterial cells, high in essentially unavailable carbon and nitrogen, becoming under suitable geologic conditions a source of peat, coal, or petroleum.

FOREST SOIL AS A CULTURE MEDIUM

Soil microbes and roots live in a colloidal complex of organic and inorganic materials more or less saturated with air and water and supported by soil particles. This physical-chemical-biological complex is in unstable equilibrium with vital phenomena and is continually changing with changes in the environment. Microbes are particularly important in this medium because they transform potential fertility into active fertility that supplies nutrients in available forms. To do this, they require nutrients, which they consume more readily than do higher plants. Any food element in limited supply may be so extensively used by microbes that little or none may be immediately available to plant roots; thus the dictum, "feed the soil, then the plant."

Infiltration of the end products of surface decomposition influences soil formation and soil morphology. Treatments that incorporate residues and fertilizers into soil hasten mineralization of organic matter to the advantage of plant growth. Humus under natural conditions is distributed from the soil surface downward in decreasing concentration, proportionately affecting the distribution and activity of the native microflora. In soil supporting living plants, microbial populations and activities are especially concentrated in the rhizosphere and extend downward on old dead roots.

ENVIRONMENTAL FACTORS

The entire ecosystem is in a state of dynamic balance with six environmental factors that affect growth and activities of soil microbes: water, temperature, aeration, pH, food supply, and biological factors. These are all interrelated; a change in one induces change in others. The production of forest residues and treatment of those residues can influence each of these factors drastically. As a result, the entire soil microbiota can shift in another direction.

1. Water. The optimum for microbial activity is almost 50 percent of soil water-holding capacity. As moisture decreases, growth slows until, in air-dry soil, the organisms become inactive. Excessive moisture reduces air supply and retards microbial metabolism. The kind of forest residue present on a site and, more important, the way it is treated can greatly affect this factor, especially the rapidity with which the upper soil layers dry out during the summer. Obviously, the rate of drying is affected by climate and vegetation as well as residue treatments. Residues in wet spots may remain saturated much of the year and decompose extremely slowly. Soil moisture loss in summer would have a greater impact on microbial activity under ponderosa pine *(Pinus ponderosa* Laws.) than similar loss under Sitka spruce *(Picea sitchensis* (Bong.) Carr.).

2. Temperature. Each micro-organism has an optimum temperature for growth and a range outside of which growth ceases; the optima can vary within certain limits, depending on other environmental factors. The population of soil organisms in any given forest would be comprised primarily of those well adapted to the prevailing temperature regime. Radical changes of the forest soil temperature regime resulting from clearcutting or residue treatments, such as burning, can engender equally radical changes in microbial populations. Such effects are likely to be most pronounced in the uppermost soil layers, where temperatures are strongly influenced by solar radiation exchange.

3. Aeration. Free oxygen (O_2) and carbon dioxide (CO_2) are vital in microbial metabolism. Although all bacteria require at least a trace of CO_2 to initiate growth, the compound is also produced as a respiration product which, accumulated in excessive amounts in the soil, can retard microbial activity. Gaseous nitrogen (N_2) is used by N_2-fixing bacteria and algae; an adequate supply of air in soil is important to maintenance of soil fertility. Good soil ventilation is required for satisfactory exchange of these gases with the atmosphere. Any residues that impede aeration and any residue treatments that compact or encrust the soil surface will reduce microbial activity, not only by restricting O_2 supply but also by allowing accumulation of toxic concentrations of CO_2.

Deep accumulations of duff,[1/] unless compacted or waterlogged, are unlikely to inhibit aeration sufficiently to impede microbial action. Abundant microbial development was found in unusually deep duff layers under a virgin Sitka spruce stand close to the Oregon coast by Bollen and Wright (1961). There would seem to be no limit to the desirable amount of duff accumulated normally. Neither would a layer of slash chips be likely to interfere with aeration if it was distributed by blowing.

4. pH. Soil microbial activity is strongly related to soil acidity or basicity (usually expressed as pH value). Forest soils are typically acid, i.e., have a pH of less than 7. Some micro-organisms thrive only in a very narrow pH range, whereas others tolerate extremes. The micro-organisms of a forest soil will be predominantly those adapted to the acidity of that soil. Radical changes in soil acidity, such as after burning of forest residues, or excessive leaching, can result in strong shifts of microbial populations. Microbes with a narrow pH

[1/] The term, "duff," is used more or less loosely to designate the surface accumulation of litter and often includes some of the immediately underlying decomposing material, especially when dry (see fig. 2, p. B-9). In older reports, components of the forest floor are designated "litter," "duff," and "leaf mold."

tolerance will be largely replaced by those with a wide tolerance plus those whose narrow pH range encompasses the new pH of the soil. This could cause some changes in physiological activities. Functions of the replaced organisms would, in general, be similar, if not the same, as those taking their place.

5. Food supply. Microbes require the same essential nutrient elements as do higher plants but often in quite different proportions. The quantities required, in keeping with the minute size of microbes, are correspondingly small per individual except for relatively large amounts of energy sources. Bacteria are comparatively inefficient in using energy; they waste much in the form of heat and incomplete oxidation. Almost any substance can be attacked by some microbe under favorable conditions. Forest residues, of course, expand the food base for microbial activities. The long-term results--nutrient recycling, breakdown of organic matter and its incorporation into the soil--will most often be beneficial. Deleterious, short-term effects can also develop, however. Although an abundant source of carbon is desirable, markedly expanded activity by organic matter decomposers can cause a temporary, severe deficiency of readily available soil nitrogen. The nitrogen is used in production of microbial cells and is not released for use by higher plants until death and decomposition of the cells outpaces new cell formation. For optimum rate of decomposition the ratio of readily available carbon-to-nitrogen should be about 25:1 (Bollen 7969). In tree residues, the ratio is much wider but most of the carbon is in resistant ligno-celluloses (table 1) that are attacked very slowly and exert only a

Table 1.-- *Proximate analyses of Douglas-fir bark, wood, and needles compared with alfalfa hay and wheat straw*

(In percent, ovendry basis)

Chemical characteristic	Bark	Sapwood	Heartwood	Needles	Alfalfa hay	Wheat straw

[1]*Not expressed as percent.*

[2]*Approximate: bused on C = 50 percent.*

[3]*Not typical wood cellulose or lignin.*

correspondingly slow nitrogen demand that can 'be supplied by slow release from humus and decomposing dead microbes. This means that for rapid decomposition of most residues, except those which are high in nitrogen like alfalfa (table 1), fertilizer nitrogen must be added to satisfy needs of microbes involved. Alfalfa contains more than enough nitrogen so that the excess soon is released as ammonium. On the other hand, humus and soils, although having a narrow carbon-to-nitrogen ratio (table 2), decompose very slowly because the organic matter is already highly decomposed and the residue is resistant to further microbial' attack.

Table 2.--*Chemical analyses* of soiZ under red *alder and* conifer stands ***on*** Astoria *silty clay loam soil (samples* taken *in April)*

Stand layer, horizon	Water	pH	Nitrogen: Ammo-nium	Nitrogen: Ni-trite	Nitrogen: Ni-trate	Nitrogen: Kjel-dahl	Total carbon	C:N ratio
Alder stand:								
L	--	--	--	--	--	1.83	51.13	28
F	239.1	3.7	190	0.07	283	2.22	40.23	18
A11	162.1	3.5	45	1.20	164	1.48	25.18	17
A12	109.0	3.9	5	.18	91	.76	13.47	18
B	83.5	4.5	5	.05	19	.35	5.92	17
Conifer stand:								
L	--	--	--	--	--	1.30	42.34	33
F	158.1	5.0	120	1.43	89	1.06	26.31	25
A11	92.0	4.8	30	.39	74	.84	18.39	22
A12	101.5	4.8	8	.19	66	.69	14.92	22
B	102.0	5.1	5	.05	15	.69	14.26	21

6. Biological factors.--Interactions between organisms are prominent features of the soil microbial complex. Competition for water and nutrients is continuous and sometimes limits development of certain species. As noted above, changes in the soil microhabitat from timber harvest or residue treatment can change competitive relationships. Many soil organisms produce products that inhibit others; penicillin and streptomycin are classic examples. On the other hand, byproducts of one species often provide food for others. Parasitism of one micro-organism on another is a common phenomenon, e.g., by bacterial viruses and predaceous fungi. Residues and residue treatments will exert indirect effects insofar as they influence the establishment of higher plants. For example, establishment of *AZnus* or *Ceanothus* species following burning will provide host roots for symbiotic, nitrogen-fixing organisms. Treatments that encourage herbaceous plants or brush species such as *Acer* or *Rubus* will similarly encourage development of roots for rhizosphere organisms and for host tissue for endomycorrhizal fungi in the family *Endogonaceae*. Like other root-inhabiting fungi, their mycelial extensions into the soil extend the nutrient absorbing power of their host plant roots.

Any one of the foregoing factors may become inhibiting when varying from an optimum range. For example, nitrification as well as general microbial activity and leaching would be limited by low summer rainfall; in winter, when temperature is low or ground is covered with snow, leaching can occur but nitrification is inhibited and all micro-organisms are only slowly active.

Cardinal values applicable in general for the environmental factors are shown in table 3.

Table 3.--*Factors of environment and their approximate cardinal values for genera2 microbia2 activity in soil*[1]

Factors	Minimum	Optimum	Maximum
Moisture	5 percent[1]	50 percent[1]	80 percent[1]
Temperature	2" C	28" C	40" C
Aeration	varies	at 50 percent[1] H_2O	varies
pH	4	7	10
Food supply	varies	balanced, C/N = 25/1	varies
Biological	--	symbiosis; limited antibiosis	--
Inhibiting	Positive or negative' extremes of other factors		

[1] Of moisture capacity.

KINDS AND NUMBERS OF MICRO-ORGANISMS IN SOIL

Almost any kind of microbe may be found in the soil (Benjamin et al. 1964). Microbes differ widely in size and shape and range from ultramicroscopic viruses to relatively gigantic fungi with spores easily visible to the unaided eye. A variety of these forms often is found in the same physiological group, producing similar chemical transformations with characteristic end products.

Bacteria are important components of the soil microflora because they grow and transform matter more rapidly than other soil organisms. Certain actinomycetes are important as the endophytes, or plant-inhabiting microbes, of nitrogen-fixing root nodules, and many species produce potent antibiotics. Soil molds are prominent in decomposition processes; many species produce antibiotics, and some are important parasites on other fungi. Mycorrhizal fungi are root symbionts of higher plants and play vital roles in nutrient absorption by their hosts. Several molds and higher fungi are root pathogens.

These organisms occur in phenomenal numbers in the soil. Table 4 and figure 1 give examples of populations in a silty clay loam soil under different

Table 4.--*Approximate masses of organisms in a fertile soil*

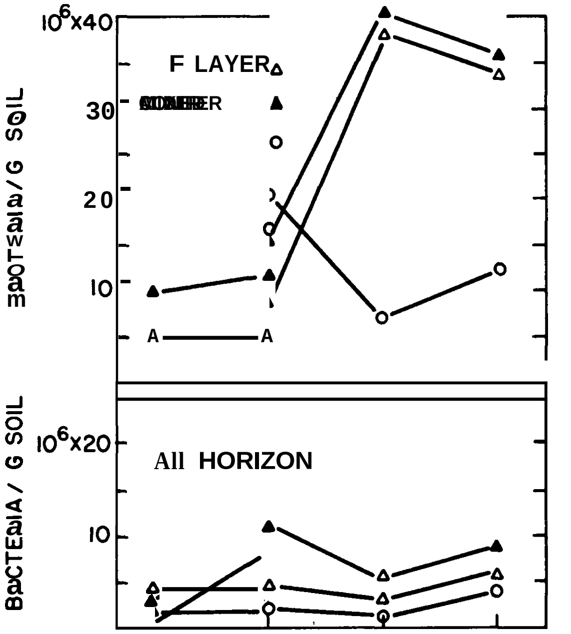
Organism	Live weight per acre to 6-2/3-inch depth 1/	Relative numbers
	Pounds	*Percent*
Bacteria	1,000	80-20
Actinomycetes	1,000	20-70
Molds	2,000	1-10
Algae	100	1
Protozoa	200	2
Total	4,300	
Dry weight =	1,000	
Nematodes	50	
Insects.	100	
Worms	1,000	
Plant roots (dry weight)	2/ 2,000	

1/ Nominally 2,000,000 pounds.

2/ Varies widely with kinds and numbers of plants, and soil type.

stands at Cascade Head. The highest populations in forest soils occur in the F horizon, the "fermentation layer" where leaves, twigs, and other residues are undergoing active microbial decomposition (Lu et al. 1968) (fig. 2). This horizon or layer may range from a small fraction of an inch to approximately 2 feet, varying with forest stand, soil type, and climate. Microbes are most abundant and most rapidly acting here. The surface layer of mineral soil may contain 10 million to 100 million bacteria (including actinomycetes) per gram and 1,000 to 100,000 molds per gram. These estimates are conservative, especially for molds, because available methods fail to detect many forms present. Numbers decrease rapidly in lower horizons.

The total living microbial mass, more significant than numbers, of the top 6 inches (15.24 cm) of an acre (0.4 ha) of fertile soil has been estimated to approach 1,000 lb (453.6 kg) each of bacteria and actinomycetes and 2,000 lb (907.2 kg) of molds, dry basis (table 4) (Bollen 1959).



of bacteria in F and A11 horizons under three different stands on Astoria silty clay loam soil.

Similar populations may be found in agricultural soils; but they are influenced more by a variety of cropping, tillage, and cultural practices.

These values represent average conditions; they would differ under different ground covers, climatic conditions, and soil types (table 5) (fig. 1). More extensive examples, encompassing 12 different soils and showing wide differences between soil types and climates, have been presented by Bollen and Wright (1961). Bollen et al. (1967) reported comprehensive seasonal changes in microbial and chemical properties in different horizons under conifer, alder, and mixed stands on Astoria silty clay loam soil at Cascade Head, Oregon.

Other organisms in forest soils deserve mention as "partners" of microbes. Nematodes, insects, and worms of various kinds are generally common in soils. They participate with microbes in decomposing organic matter, mixing it with the soil, and rendering it more susceptible to microbial attack. Their waste substances are utilized by microbes, they transport microbes on or within their bodies, and they enhance microbial activity by increasing soil permeability (Jacot 1936, Macfadyen 1968). Earthworm activity mixes surface material with the mineral soil and increases aeration and drainage. Certain larger insects, such as wood borers and bark beetles, contribute to residue deterioration, not only directly but also by transporting microbes into the channels made. Bacteria are often linked with tree-destroying fungi (Anonymous 1972b). Fungi and minute insects are important in the preliminary deterioration of forest residues. The role of higher fungi is discussed by Aho (1974); biological and sequential aspects are covered.

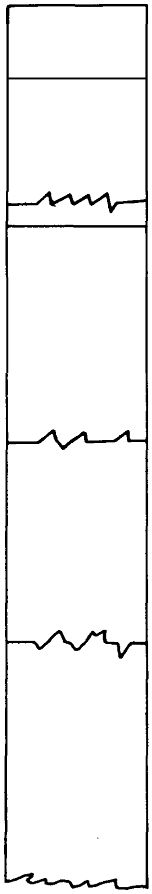
Roots deserve special consideration as a biological component of the soil. A narrow zone, designated as the rhizosphere, approximately 1 mm wide and surrounding living roots, is especially favorable to development of bacteria; 75 to 90 percent of the total microbial population of a soil occurs in this zone.

Table 5.—*Molds in F layer and All horizons under three different stands on Astoria silty clay loam soil*

Stand and layer, horizon	Water	Water-holding capacity	Loss on ignition	pH	Molds					
					Total	*Mu-aorsl/*	*Asper-gilli*	*Peni-aillia*	*Trioho-derma*	Others
	-----	Pevoent	-----		*i/M/g**	----------		Percent	---------	
Alder stand:										
F	193	418.8	62.4	3.6	225	0	0	33	67	0
All	98	196.3	30.4	3.9	73	13	0	40	37	10
Conifer stand:										
F	135	292.5	44.0	5.1	709	27	0	41	0	32
All	105	205.8	34.1	5.3	195	19	8	39	0	34
Mixed stand:										
F	135	303.3	45.0	3.9	291	20	3	54	0	23
All	90	184.5	28.6	4.3	79	23	5	49	0	23

1/ **Included** *Rhizopus*, *Mucor*, *Mortierella*, and other genera of the Mucorales.

2/ Thousand **per** gram of soil.



01 Invertebrate fauna, microbes, and higher fungi active (L),[1/] (litter),[1/]

02 Region of greatest microbial activity (Aoo),[1/] (F),[1/] (fermentation).[1/]

H Featureless, highly decomposed organic matter; found in mor soils of cold regions. Not in mull soils. Mor humus. Characteristic of Podzols. Limited microbial activity.

A Mineral horizons. May be subdivided into Al, A2, etc., according to transitional features and humus concentrations. Top soil. Microbial activity decreases with depth.

B Subsoil. Contains illuvial concentration of clay, iron, aluminum, or humus, alone or in combination. May be subdivided into transition zones B1, B2, etc. Minimum microbial activity. Acts as a microbial filter.

C Parent material from which the soil profile is formed. Unconsolidated rock, sand, peat, etc. Essentially no microbial activity.

1/ Alternate or obsolete designations.

Figure 2.--Forest soil horizons. Depth of horizons or layers which constitute the profile vary by forest type, vegetation, drainage, climate, and parent material. For complete descriptions, see Glossary of Soil Science Terms, Soil Science Society of America, Madison, Wis., 33 p., illus., 1973.

This is attributable to the enormous extent of root systems and their root hairs, which have a calcium-pectate surface layer, and to the metabolites liberated at the surfaces. These metabolites include sugars, organic acids, and other compounds that provide readily available nutrients for many micro-organisms. On the other hand, some of the exudates liberated by roots of white pine (*Pinus strobus* L.) may be inhibiting to certain microflora (Slankis et al. 1964). Significance of these interactions, especially in root pathogens, deserves further study.

The extent of root systems and their surface exposure is little appreciated. An exhaustive study by Dittmer (1937) of one rye plant grown in 2 ft^3 (56.6 dm^3) of a silt loam soil revealed the following:

13,800,000 roots: total length, 387 miles (622.7 km); surface area 2,554 ft^2 (237.4 m^2)

14×10^9 root hairs: total length, 6,600 miles (10,679 km); surface area, 4,320 ft^2 (401.5 m^2).

Compared with the total external surface of shoots and leaves, which was 51.38 ft^2 (4.78 m^2), the root exposure was 130 times that of the aerial parts.

The 2 ft^3 (56.6 dm^3) of soil, 145 lb (65.8 kg), had a total particle surface of 70×10^6 ft^2 (1,607 acres (650.4 ha)). Thus the total root surface was only 0.01 percent of the surface available in the soil, indicating roots make little contact with the soil.

The few studies made on forest tree roots have been less comprehensive. However, for white spruce (*Picea glauca* (Moench) Voss) 10,000 linear feet (304.8 m) of root in a sandy loam soil was related to 10 ft^3 (0.28 m^3) of volume in the trunk; in clay the relationship was 5,000 ft (1,524 m) of root to 10 ft^3 of trunk (Anonymous 1967). McMinn (1963) reported 464 ft of roots greater than 1 cm in diameter for a 55-year-old dominant Douglas-fir.

Dead roots are important because they support microbes active in decay and mineralization in deeper soil strata. After decay is complete, the root channels provide drainage and aeration.

ORGANIC MATTER AND NITROGEN--CARBON AND NITROGEN CYCLES

Organic matter is the cream of the soil. It is a storehouse of available and potential nutrients, improves soil structure, increases water-holding capacity, buffers against changes in pH, and adsorbs cations, such as ammonium (NH_4^+) and calcium (Ca^{++}), against leaching even though they remain available to microbes and roots.

Bacteria and other microbes which attack plant and animal remains break them down into simple substances plants can use. Like animals, they are destructive feeders. They bring about decomposition or decay, which is an essential sequel to life. From the standpoint of plant nutrition, this may be considered a predigestion of plant food. It is performed by many unspecific bacteria and by a few specialized bacteria capable of attacking particular substances. In some instances, the bacteria act as scavengers in decomposing materials that might be toxic to plants.

Forests annually contribute about 16×10^9 metric tons (17.6 tons) of carbon as organic matter (Riley 1944) to the global production on the soil as shown in figure 1. Thus forest residues account for nearly 75 percent of the total carbon recycled each year from the total land surface.

Building-up processes in the soil are brought about by those bacteria which may be considered constructive feeders. Two types may be recognized: autotrophs--strictly mineral feeders which, like plants, build their organic substance from carbon dioxide and water and semimineral feeders or nitrogen-fixers, which require complex carbonaceous food but can utilize nitrogen in elemental form. The significance of strictly mineral feeders lies in their ability to obtain energy by oxidizing simple mineral substances--such as hydrogen, methane, ferrous iron, and especially ammonia--to nitric acid and sulfides or sulfur to sulfuric acid, This action not only changes decomposition products to available plant food but also dissolves soil minerals, rendering them available.

The ecological significance of these two groups can be appreciated from a brief consideration of the cycles of carbon (fig. 3) and nitrogen (fig. 4) (Bollen 1959, 1967). In the carbon cycle, carbon dioxide from the atmosphere is converted by autotrophs into organic compounds of high energy content. Photosynthetic organisms obtain energy for this transformation from the sun's rays. The autotrophic bacteria derive energy from oxidation of certain elements, such as sulfur or hydrogen, or from oxidation of simple compounds such as ammonium, hydrogen sulfide, or carbon monoxide. Heterotrophs consume organic energy-containing substance previously synthesized by autotrophs and other heterotrophs; this biological material is used for both structure and energy, the greater proportion being oxidized for energy and therefore yielding much carbon dioxide, which returns to the cycle. During photosynthesis, CO_2 is consumed and O_2 is evolved. Thus all green plants, and forests especially, make it possible for us to live here. Also, all living cells give off CO_2 during respiration, and this is returned by trees and other green plants to the atmosphere during dark periods. Due to the supply of juvenile CO_2 from volcanoes and mineral springs, which supply over 90 percent of the CO_2 in our atmosphere, and to the $CO_2 + CaCO_3 + H_2O \rightleftharpoons Ca(HCO_3)_2$ buffer action in the oceans, the supply of CO_2 is maintained remarkably constant at 0.04 percent, by weight. This and the O_2 supply and other chemical factors in the environment are additionally subject to biological control by reciprocal interactions of organisms and their external conditions (Redfield 1958).

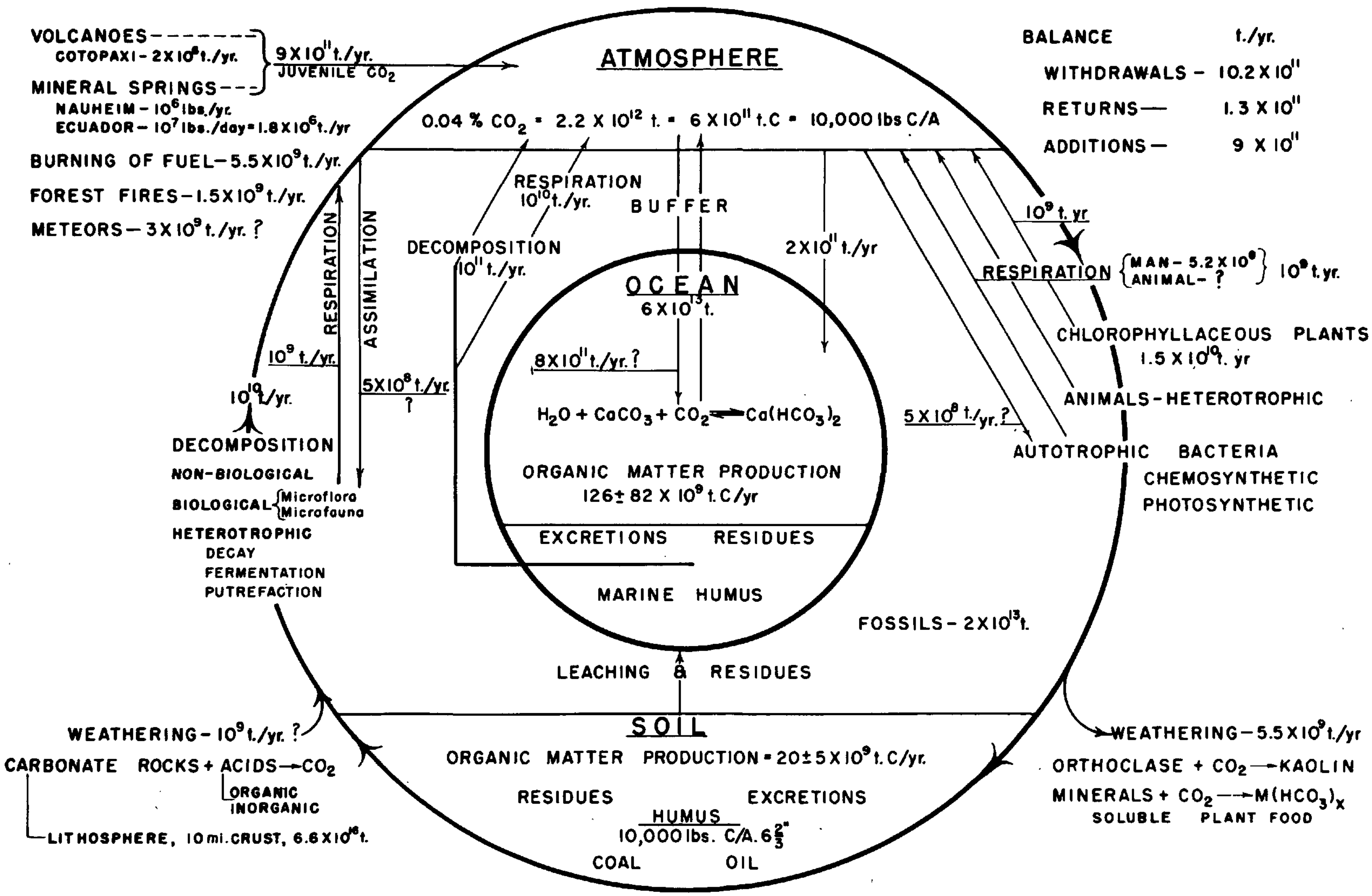
An additional phase (not illustrated in fig. 3) of the carbon cycle involves CO. This is discussed under "Burning."

In the nitrogen cycle, proteins yield ammonia (NH_3), upon decomposition by a wide variety of bacteria, actinomyces, and molds. NH_3 rapidly combines with water to become NH_4OH, yielding ammonium (NH_4^+). Ammonium is oxidized to nitrite (NO_2^-) and nitrate (NO_3^-) by autotrophic nitrifying bacteria. Nitrite occurs in a very limited concentration, rarely more than 2 p/m., in soils. It is converted by nitrifying bacteria to NO_3^- more rapidly than NH_4^+ is oxidized to NO_2^- by nitrosofying bacteria. Nitrification is especially rapid under red alder (*Alnus rubra* Bong.) (Bollen and Lu 1968). Only when nitrifiers are absent, which is rare, or when NH_4^+ concentrations exceed about 100 p/m and become toxic to nitrifiers does NO_2^- accumulate to any extent. High concentrations of NO_2^- become toxic to plants under most conditions.

Examples of the influence of stand and season on the nitrogen transformations in F and All horizons are given in figure 5. Table 2 shows differences in all horizons for samples taken in spring. Nitrate, as well as some NH_4^+, is assimilated by plants and microbes and converted to amino acids ($H_2N-R-COOH$) (where R represents CH_3^- or other organic groups), then to proteins, which are highly complex polymers of amino acids, thus completing the cycle. Protein metabolism by animals extends the cycle without greatly altering the fundamental mechanism.

An additional, important phase is biological dinitrogen fixation. This converts free nitrogen (N_2) to NH_4^+, amino acids, and cell protein. Assimilation

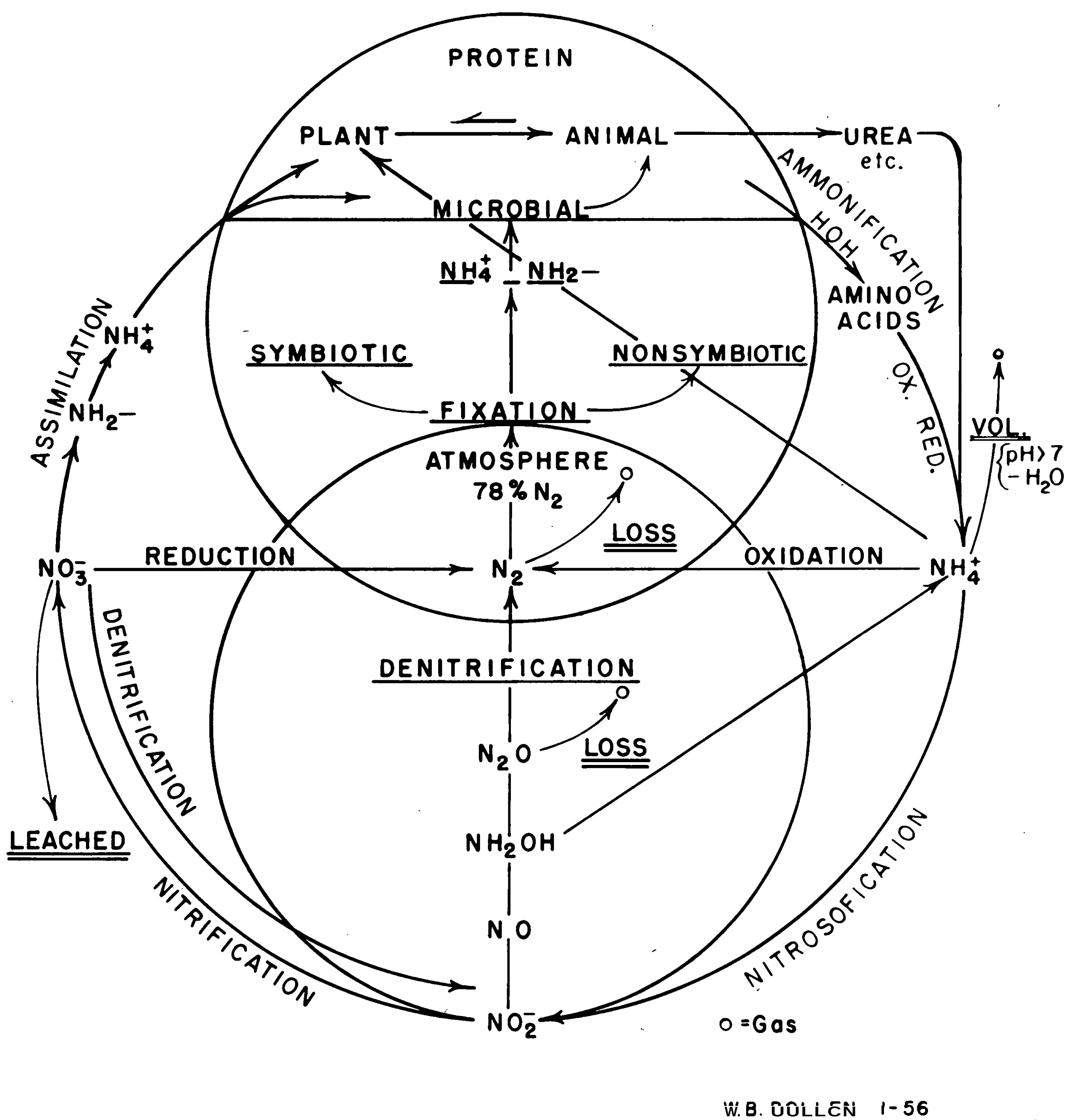
Figure **3.-- THE CARBON CYCLE**



Data In Metric Tons CO_2 Except C As Indicated

W. B. BOLLEN, 1958

Figure 4.-- NITROGEN CYCLE



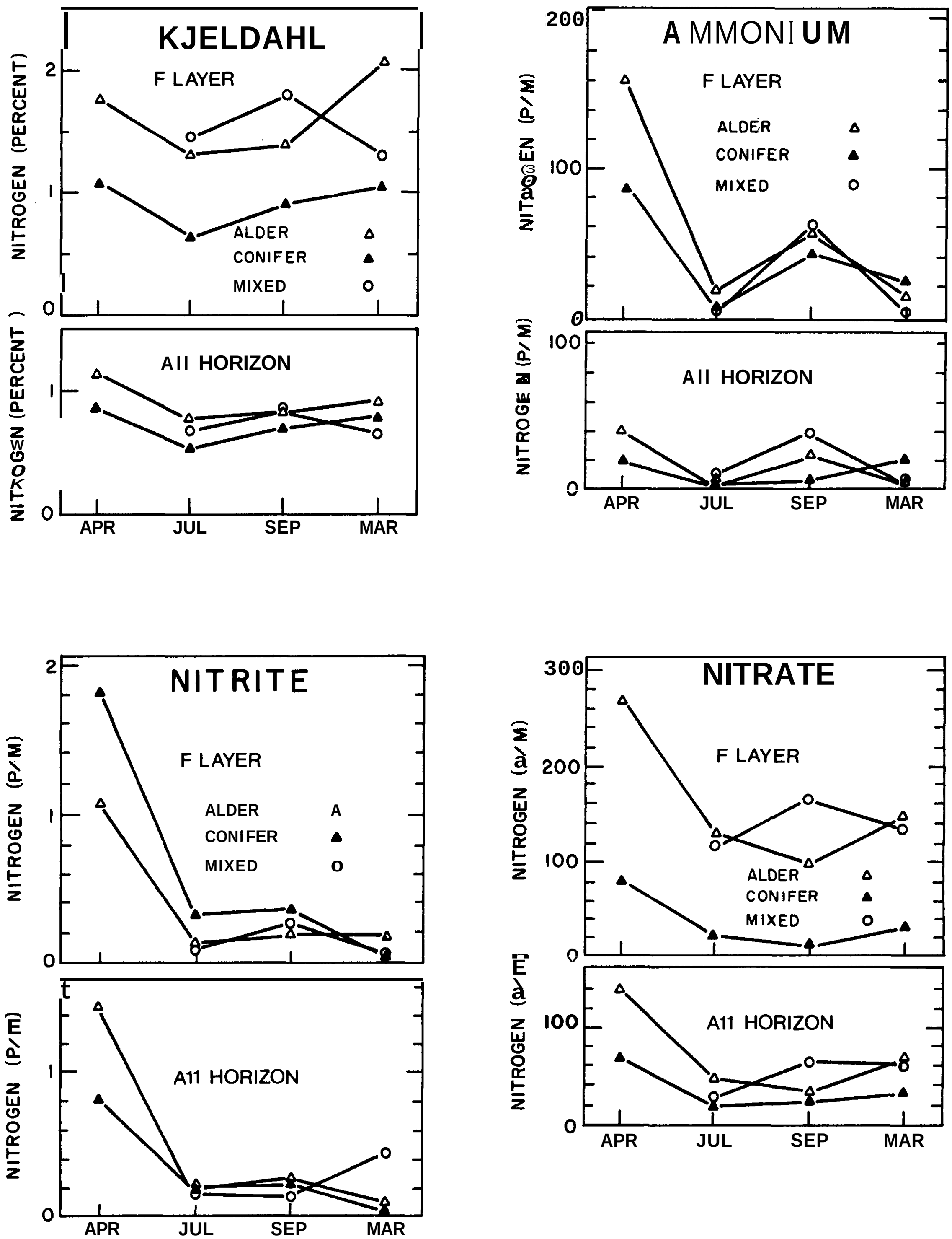


Figure 5.--Seasonal changes in nitrogen status in F and A11 horizons under three different stands on Astoria silty clay soil.

of elemental nitrogen is an ability possessed only by a few bacteria, mainly heterotrophs, and by certain blue-green algae. Nonsymbiotic fixation is carried on by *Azotobacter* and certain species of *Clostridium*. Upon death of the cell, the protein reenters the cycle and becomes subject to ammonification. Species of *Rhizobium* carry on fixation only when living symbiotically in nodules on roots of leguminous plants--much of the fixed nitrogen being NH_4^+ and amino acids, immediately available to the host. Of the total nitrogen-fixation by both *Azotobacter* and *Rhizobium*, a considerable part is liberated in soluble extracellular organic form during the life of the cell; some ammonium is also liberated. Thus nitrogen-fixing bacteria convert the generally unavailable gaseous nitrogen into immediately available compounds as well as into nitrogenous tissue which must be decomposed later by other organisms before becoming active in fertility.

Were it not for these bacteria, the vast supply of N_2 in the atmosphere would not become available to other organisms. Trace amounts are converted to NO_3^- by lightning and other electrical discharges, and traces of NH_4^+ are formed by some nonbiological processes, but the amounts are minor compared with biological fixation. Most of the combined nitrogen in the atmosphere comes from the combustion of fuel. The total amount of NO_3^- and NH_4^+ brought to the earth by precipitation averages about 5 lb/acre (5.6 kg/ha) N-equivalent per year. Nonsymbictic fixation varies with soil type, cultural practices, and climate. The average N_2 fixation is near 5 lb/acre (5.6 kg/ha) per year and may only offset leaching losses. Symbiotic fixation by cultivated leguminous plants, such as alfalfa, may exceed 200 lb (224 kg/ha), whereas fixation by alder ranges from 50 to 185 lb/acre (56 to 207 kg/ha) per year (Tarrant 1968, Bollen and Lu 1968).

N_2 fixation by the symbiotic association of microbes with plants is undoubtedly the most important source of fixed nitrogen in nature. However, the broad distribution of free-living N_2 fixers, especially certain blue-green algae and photosynthetic bacteria, is an important contribution to soil fertility. Estimates range from 5 to 20 kg/ha (4.5 to 18 lb/acre) per year (Dalton and Mortenson 1972) for agricultural soils. The significance of nonsymbiotic N_2 fixation in forest soils should be investigated.

Recently, N_2-fixing bacteria have been isolated from decay caused by fungi on white fir (*Abies concolor* (Gord. and Glend.) Lindl.) trees (Seidler et al. 1972) Possibly these bacteria supply the fungi with nutritional forms of nitrogen. If so, then development of some means of inhibiting the bacteria or their N_2-fixing capability could provide a control of the fungi. Discovery of these bacteria suggests that the possibility of N_2 fixation by other bacteria occurring in living trees (Bacon and Mead 1971) should be examined. Cornaby and Waide (1972) found N_2-fixing bacteria in decaying chestnut logs; they suggest that nitrogen fixed by organisms inhabiting decaying woody tissue is an important part of the total nitrogen input to forest ecosystems.

Losses of nitrogen from the soil occur by erosion, leaching of nitrate, or by volatilization of ammonia under moist, nonacid conditions, by assimilation by plants, and by denitrification. These losses are especially important because available nitrogen is most frequently the limiting plant nutrient in soils. In this connection, the cation exchange capacity (CEC) is significant. It consists of organic matter and colloidal clay. The organic matter is especially important because it comprises a major fraction of the CEC of soils. Different soils and residues vary in CEC largely because of differences in organic matter content. Examples are shown in tables 6 and 7. Importance of the CEC lies in its capacity to hold nutrient cations, particularly NH_4^+, against leaching although they are readily available for assimilation by roots and microbes. Nitrate, being an anion, is not held and can be rapidly leached.

Table 6.--*Lime requirement, exchangeable cations, and available boron in A11 horizon under three different stands on Astoria silty clay loam soil*

Stand and pH	Lime requirement to pH 6.5	Cation-exchange capacity						Available boron
		H+	Ca++	Mg++	K+	Sum of cations	Total	
	Tons/acre	*Milliequivalents per 100 grams of soil*						*P/m*
Alder stand:								
3.9	25	45.1	3.8	8.6	8.1	65.6	68.1	1.19
Conifer stand:								
5.3	11	30.4	12.5	16.0	5.2	64.1	69.0	7.83
Mixed stand:								
4.3	17	40.6	2.3	8.2	9.3	60.5	65.4	1.79

The forest floor may have a higher total CEC than several inches of the underlying mineral soil (Wells and Davey 1966). For the forest floor from different Douglas-fir plant communities in the Oregon Coast Ranges, Youngberg (1966) found CEC values ranging from 54.4 to 75.8 meq/100 g, the differences being associated with different understory vegetation.

Denitrification occurs when available oxygen (O_2) in the soil becomes limited and NO_3^- or NO_2^- and oxidizable substances are present. Under these conditions, certain anaerobic and facultatively anaerobic bacteria use the NO_3^- or NO_2^- as oxidants to catabolize oxidizable substrates and obtain energy for growth. Nitrate is reduced to NO_2^-, NO_2^- to nitric oxide (NO, gas), then to hydroxylamine (NH OH) which becomes reduced to nitrous oxide (N_2O, gas) and finally N_2 (gas)? The gases are lost to the atmosphere. The sequence may occur in various combinations. In some cases it stops at NO_2^-; if O_2 becomes available loss does not then occur, and nitrification can reoxidize the NO_2^- to NO_3^-. Limited amounts of denitrification can occur even in well-aerated soils, where there always are microclimates of anaerobiosis existing within groups of O_2 consuming aerobes surrounding particles of substrate.

Table 7.--*Cation exchange capacity (CEC) of some organic residues and soils*

Material	Mesh size[1/]	CEC
		Meq/100 g
Douglas-fir:		
Bark	+5	44.8
Bark	-10+40	39.7
Bark	-40	60.5
Wood	-10+40	39.5
Wood	-40+100	28.2
Wood	-100+200	15.0
Red alder:		
Bark	-10+40	40.4
Wood	-10+40	59.0
Wood	-100+200	7.5
Ponderosa pine wood	-10+40	13.5
Wheat straw	-10	39.4
Delhi loamy sand	-10	2.7
Walla Walla silt loam	-10	18.6
Chehalis silty clay loam	-10	24.3

1/ Tyler standard sieves.

Soil nitrogen is depleted only by leaching, denitrification, and assimilation by microbes and plants. Nitrogen tied up by microbes is eventually returned when they die and become decomposed by succeeding generations. Nitrogen assimilated by plants is lost to the system where the trees or other plants are removed from the site. When these or their residues decay on the site, their nitrogen returns to the soil as decomposition products and in dead microbes that effected the decomposition.

Table 8 shows some of the important physiological groups of bacteria, their functions, and range of typical numbers.

Table 8.--*Kinds, numbers, and significant functions* of *microbes in soil*[1]

Kinds	Numbers/gram	Functions	Remarks
	Millions		
Heterotrophs:			
Oxidative	10-100	Completely oxidize organic matter	Active only in presence of free O_2
Fermentative	10-100	Partially oxidize organic matter	Active in absence of O_2; may be facultatively oxidative
Proteolytic	10-100	Decompose proteins to amino acids	
Ammonifiers	10-100	Oxidize amino acids to NH_4^+	Aerobic, anaerobic, and facultative. Include most proteolytic species
Denitrifiers	1-10	Oxidize organic matter with NO_3^- or NO_2^-. Release N_2 or gaseous N oxides. Assimilate N_2	Function in absence of O_2
Nitrogen fixers	1-10		Aerobic species often limited by pH<5.5. Anaerobes less sensitive. Symbiotic species adapted to pH of host
	Thousands		
Autotrophs:			
Nitrosofiers	1-10	Oxidize NH_4^+ to NO_3^-	Often inhibited by pH<5
Nitrifiers	1-10	Oxidize NO_2^- to NO_3^-	Sensitive to acidity; inhibited by excessive NH_4^+
Sulfur oxidizers	1-100	Oxidize H_2S, S, etc., to $SO_4^=$	Most species favored by or tolerate very low pH

1/ Table generalized and necessarily incomplete for the present discussion. The various groups not only occur simultaneously but more or less overlap according to substrate and environmental conditions.

For a more complete discussion of the carbon cycle see Bolin (1970); for the nitrogen cycle, Delwiche (1970). Other elements undergo similar cycles, but some different microbes are involved. An extensive description of the sulfur cycle is given by Kellog et al. (1972). Mineral cycles are described by Deevey (1970). Oxygen, originally derived from photosynthesis, is fundamentally important in energy-yielding reactions. Its cycle has been well described by Cloud and Gibor (1970). All these cycles occur simultaneously and often involve the same substrates where a great variety of organisms carry on their life functions.

KINDS OF FOREST RESIDUES AND MICROBIAL ACTIVITIES

Particle size, nitrogen content, presence of microbial-resistant compounds, moisture content, and aeration are particularly critical factors in rate of forest residue decomposition. The finer the particle, the greater is its surface exposure to microbial attack (Neal et al. 1965). An optimum size particle is difficult to define. Too fine a particle restricts aeration and percolation; too large retards decomposition. An ideal product would be a mixture of shapes and sizes ranging from one-fiftieth to one-eighth inch (approximately 32- to 6-mesh screen size). The importance of size and shape of particles in relation to use on the soil has been discussed in a previous paper (Bollen 1969; p. 8, 15, 18).

The higher the nitrogen content, within reasonable limits, the greater is the potential for microbial activity and reproduction. Thus for a given particle size, leaves, with their relatively high nitrogen content, are more rapidly decomposed than wood which has a low nitrogen content and contains resistant lignocellulose complexes (Bollen and Lu 1957). Wood, in turn, decomposes faster than bark (Bollen 1969, Bollen and Glennie 1961). Water-soluble materials (tables 1 and 9) are decomposed rapidly, but ligneous materials are attacked slowly by specialized bacteria and fungi. Composition of residues--particularly nitrogen, water-solubles (table 9), cellulose, and lignin--influence rates of decomposition under any given conditions (compare with table 1). Bark contains more nitrogen than wood, has generally less water-soluble material, and the lignocelluloses are different, accounting for slower decomposability.

Total nutrients in residues (table 10) indicate potential returns to the soil upon complete decomposition, though not necessarily the rate of return. The rate is determined by quality, which depends upon proximate analyses (table 1).

Young and Guinn (1966) give comprehensive analyses for nitrogen and ash constituents, including trace elements, in needles or leaves, branches, trunks, and roots of four conifers and three hardwood species of Maine. Pitchwood seams remain intact long after the other wood has disintegrated; the limiting factor in this case is probably aeration, since finely divided pitch is rapidly attacked (Bollen and Glennie 1961). Under similar conditions, different species of barks and woods decompose at different rates (table 11) (Allison 1965, Bollen 1969).

In the Pacific Northwest, moisture-temperature relationships are critical in controlling rates of microbial activity on residues. During the winter and spring, residue moisture contents are good for microbial activity but temperatures are below optimum. During the summer and autumn, temperatures may be optimum for

Table 9.--*Analysis of cold-water solubles in bark and wood*

Species	pH		Water soluble[1]		Kjeldahl nitrogen		C:N ratio	
	Bark	Wood	Bark	Wood	Bark	Wood	Bark	wood
Western redcedar:								
Untreated	3.2	3.5	2.95	6.99	0.14	0.06	378:1	810
Extracted	4.5	4.6	--	--	.13	.06	392:1	835
Redwood:								
Untreated	3.2	4.4	2.35	1.67	.11	.07	473:1	753
Extracted	4.8	5.6	--	--	.11	.06	457:1	876
Red alder:								
Untreated	4.6	5.8	11.64	1.43	.72	.13	71:1	377.
Extracted	5.0	6.0	--	--	.81	.15	62:1	320
Western hemlock:								
Untreated	4.1	6.0	3.95	3.47	.27	.04	212:1	1,234
Extracted	4.4	4.4	--	--	.24	.03	223:1	1,618
Ponderosa pine:								
Untreated	3.8	4.4	4.35	2.68	.12	.04	422:1	1,297
Extracted	3.9	4.2	--		.13	.06	429:1	895
Sitka spruce:								
Untreated	4.9	4.1	10.89	1.27	.41	.04	130:1	1,214
Extracted	6.4	6.4	--	--	.40	.04	127:1	1,194
Douglas-fir:								
Untreated	3.6	3.4	5.49	4.65	.12	.04	471:1	1,268
Extracted	3.8	3.3	--	--	.11	.04	513:1	1,242
Sour sawdust	--	2.0	--	12.81	--	.06	--	893
Moss peat:								
Untreated	3.8		1.04		.83		58	
Extracted	4.4		--		--		--	

[1] *Total solids in 12 successive 1:10' water extractions, 24 hours each.*

Table 10.-- *Major plant nutrients in bark and wood (sawdust)*

(In percent, dry basis)

Material	N	P	K	Ca	Mg
Bark:					
Douglas-fir	0.12	0.011	0.11	0.52	0.01
Ponderosa pine	.12	.003	.11	.25	.01
Redwood	.11	.011	.06	.29	.00
Red alder	.73	.153	.24	1.25	.18
Sawdust:					
Douglas-fir	.04	.006	.09	.12	.01
Ponderosa pine	.04	.008	.12	.16	.02
Redwood	.07	.001	.01	.20	.02
Red alder	.37	.013	.12	.18	.04
Moss peat	.83	.030	.02	.50	.12

many microbes but low moisture becomes limiting. Wagener and Offord (1972) reported in a northern California study that unburned logging slash on two mixed-conifer sites decayed at a much slower rate than any previously studied. High summer temperatures and low summer and fall precipitation were thought to be the major limiting factors. Since the soil retains moisture, which ameliorates temperature extremes, close contact of residues with the soil can normally be expected to extend the season of most active microbial attack.

Kowal (1969) found that leached needles of *Pinus echinata* decomposed much more rapidly than unleached ones. This effect had been observed previously by King and Heath (1967) and was attributed to the removal of polyphenols by the leaching. From this it is evident that decomposition of needles in the forest floor under pine will be additionally favored during periods of heavy rainfall or snowmelt.

Thinnings, prunings, and slash are all subject to the foregoing considerations. For untreated logging residues especially, of considerable diameter and length, the surface exposure and contact with the soil are much less than for litter fall; and tremendously greater amounts of substance are left. On Douglas-fir clearcuts, coarse logging residues range from about 2,500 to nearly 20,000 cubic feet per acre (75 to 1,200 m^3/ha), weighing from approximately 30 to 230 tons (67 to 516 metric tons/ha) (Dell and Ward 1971). In western Oregon and Washington, about 63 percent of all net residue volume is in pieces 12 feet (3.66 m) or more in length, while about 82 percent is 8 feet (2.44 m) and

Table 11.--*Decomposition of* ***bark,*** *wood, and other organic materials in silt loam soil incubated at 28° C and 50 percent of water-holding capacity*

	Carbon released as CO_2 in 50 days	
	Bark	Wood
	- - - - *Percent* - - - -	
Douglas-fir:		
Young growth	26	30
Old growth	18	--
Red alder	18	40
Western hemlock	16	27
Ponderosa pine	21	33
Western redcedar	8	33
Dextrose[1/]	58	
Wheat straw[1/]	48	
Moss peat[1/]	4	

1/ Standards for comparison.

longer. In western Washington National Forests, the diameter of half of the residue pieces was 15 inches (3.8 dm) or more (Howard 1971). Such residue would require years to decompose if not burned, salvaged, chipped, or otherwise treated. As long as it remains intact, slash constitutes a fire hazard and interferes with reforestation, not to mention its undesirable appearance.

Breakdown of slash in the Sierra Nevada of California required about 30 years to transform the fire hazard from extreme, immediately after logging, to a low rating comparable to the undisturbed forest (Wagener and Offord 1972). By contrast, such a span in fire hazard conditions in the South was 6 years for hardwoods. In the Douglas-fir region of the Pacific Northwest, tops and small logs under 2 feet in diameter showed 90 percent of wood volume decayed after 16 years (Wagener and Offord 1971).

Although decomposition of residues is due largely to soil microbes, bacteria--some of, which may be N_2 fixers, already present in living trees--may play a role (Bacon and Mead 1971, Shigo 1967). Present information is insufficient to assess the significance of these organisms.

INTERRELATIONSHIPS OF SOIL MICROBES WITH RESIDUE TREATMENTS

The return of forest organic matter to the soil, whether by standing trees or by their residues after harvest, includes potenti-a1 nutrients and also increases the capacity of the soil to store nutrients. Microbes are important in this phenomenon because they render the potential nutrients slowly available, so that either or both the soil adsorptive colloidal-organic complex and assimilation by roots and microbes can absorb the nutrients before they are susceptible to loss in drainage or runoff.

RESIDUES FROM DIFFERENT HARVESTING PRACTICES

In addition to tree residues from timber harvest the forest floor has considerable volume and contains significant amounts of nutrients. Youngberg (1966) found that the forest floor in Douglas-fir stands from the Oregon Coast Ranges varied from 20,000 to 76,000 lb/acre (22 to 85 metric tons/ha) and contained from 0.71 to 1.52 percent total nitrogen. Whatever the method of logging, the soil is disturbed and residues are left. When trees are removed, when fires occur, and when vegetation is destroyed by herbicides, the release of nutrients from the soil is accelerated. In part this is due to the resulting microclimate being more favorable to rapid mineralization by the soil.microflora (Bormann et al. 1968). Likens et al. (1969) demonstrated that nitrates and other anions in stream water were considerably increased by removal of all vegetation from a forested watershed. The rate of loss is not long sustained, however, and nutrient outflows are small compared with the total nutrient reserve in the soil (USDA Forest Service 1971).

Clearcutting obviously disturbs the soil most and leaves the most residue, calling for postharvest treatment. Chunks and broken pieces could be picked up by relogging for salvage. Prelogging to remove 6- to 30-inch (15.2- to 76.2-cm) diameter trees valuable for pulp, before big trees are logged, can be done with lighter equipment and avoids the damage caused by harvesting big logs. Progressive logging in old growth removes windfalls and sound snags before the green trees are cut, reducing breakage in fall'ing. Thinning and partial harvesting of young-growth stands and harvesting of individual selected trees, as in uneven-aged pine forests, leave much less residue and disturbs the soil less. Shelterwood systems involve less area and have less effect on soil environment. Where even-aged forests are block-logged by area selection, impact is maximum but not widespread.

Greatest damage is done when skid trails and roadways remove all topsoil, causing erosion and increasing susceptibility to leaching and runoff.

Prelogging, thinning, and shelterwood methods not only conserve timber, improve utilization of old-growth stands, and result in clean-logged areas low in fire hazard, but also cause less slash and more rapid decomposition and recycling.

As young-growth trees replace harvested virgin' timber, the transition involves changes in forest residue regimes. Old-growth residues should be disposed of in a manner favorable to the establishment of new trees and decomposition and recycling of nutrients.

BURNING

Severe burns, such as wildfire and slash pile burns, can sterilize the upper soil and change soil properties (Neal et al. 1965). However, reinoculation by windblown dust and debris soon follows; and when moisture is sufficient, microbial populations can increase for a few weeks until an equilibrium is reached. Insofar as burning changes the soil properties, the microbes having advantage in a burned soil will differ from those having the advantage before burning, since for the most part effects of fire are indirect through the physical and chemical changes induced. These changes vary in degree and duration by intensity of burn, soil and climatic characteristics of the site, and kind of vegetation that invades an area after the burn.

When combustion of organic matter is complete, the end products are largely carbon dioxide, water, and ash, plus some nitrogen oxides derived from nitrogenous materials. With both wildfires and prescribed burning, oxidations in much of the affected area are usually incomplete and produce a wide variety of products (Hall 1972). Many of these, including carbon monoxide and hydrocarbons, are like those entering the atmospheres from trees and other plant life and from microbial decomposition of vegetative remains. In effect, fire compresses these normally occurring processes into a shorter time. Most of the residual products, including carbon monoxide and hydrocarbons, are consumed by certain species of bacteria and microfungi; and the elements are eventually recycled in the biosphere.

Although the contributions of carbon monoxide and hydrocarbons from slash fires to the atmosphere are appreciable (Fritschen et al. 1970), the emitted quantities add little compared with natural sources. Scientists of Argonne National Laboratory, Argonne, Illinois, have shown that at least 10 times more carbon monoxide enters the atmosphere from natural sources, including oxidation of methane and decay and growth of chlorophyll, than from all industrial and automotive sources combined (Anonymous 1972C, Maugh 1972).

Charcoal residues are highly resistant to decomposition. Pieces are commonly found in many soils. Bollen (unpublished 1931 data) found that, when 1,000 p/m of 60-mesh Douglas-fir charcoal was added to a soil in the laboratory, 14.9 percent was decomposed in 312 days, as shown by CO_2 evolution. However, most of this CO_2 was probably derived from microbial oxidation of the adsorbed hydrocarbons.

Keep in mind that most of the nitrogen is in fallen and decaying leaves of the duff; much less nitrogen is in wood and bark (table 1). Broadcast burning that consumed the duff would result in loss of most of the nitrogen to the atmosphere, largely in the form of nitrogen oxides. DeBell and Ralston (1970) found that 62 percent of the nitrogen in pine litter and green needles was released by burning. They theorized that since only minor amounts of ammonia and other nitrogen compounds appeared in the combustion gases, the majority of the nitrogen was volatilized as nitrogen gas. Piled burning and pit burning would leave much of the duff, with its greater nitrogen content subject to microbial transformation to ammonium and nitrate, which would be available to plant roots. These forms of nitrogen would disappear from the soil only by assimilation and, in the case of nitrates, by leaching.

Severe burns usually occur in small scattered patches. Only here will all organic matter be destroyed to a depth of several inches. Knight (1966), from burning experiments in the laboratory, reported 25- to 64-percent loss of nitrogen from forest floor material at temperatures of 300°-700° C. Nitrogen concentration of residual material increased, but the total amount of nitrogen decreased. Decay fungi will be destroyed in burned areas but can survive in underlying roots.

Neal et al. (1965) found that slash burning on Astoria silt loam soil significantly reduced water-holding capacity during the 1 year of study. Soil pH was increased in amounts ranging from 0.3 to 1.2 units. Increases in ammonium nitrogen were found up to 6 months after burning, but nitrate nitrogen was low at all times during the 1 year of study. Kjeldahl nitrogen declined, but total carbon increased by 1 to 2 percent; thus the C:N ratio appreciably widened. Numbers of bacteria significantly increased but fluctuated with seasonal changes. Percentage of *Streptomyces* among the bacteria was not markedly influenced. The mold population, however, was significantly reduced. At least the initial effects of slash burning on physical, chemical, and microbial properties of the soil appeared beneficial to fertility.

Accumulation of residues in forests from which fire has been excluded constitutes a fire hazard. For this reason, very light burns may be made periodically. Burning of surface material occurred naturally at intervals of about 5 to 15 years in sequoia and ponderosa pine forests before white man. Prescribed burning to remove the Aoo horizon (duff or surface litter of needles, leaves, twigs, etc.) is practiced at about 5-year intervals in pine plantations of the South. Prescribed burning in conjunction with clearcutting has been used to prepare seed beds for loblolly pine (*Pinus taedu* L.) in the Upper Piedmont of South Carolina and in mixed stands of shortleaf pine (*P. echinata* Mill.) and hardwoods. After leaffall was complete and when the duff had sufficient moisture to prevent exposure of the mineral soil, burning stimulated natural regeneration of yellow-poplar (*Liriodendron tulipifera* L.) (Shearin et al. 1972). Effects of such light burning are: (1) it stimulates germination of seeds of certain species, (2) it removes the competitive herbaceous understory, and (3) the ash is a source of newly available nutrients. Although nitrogen of the burned duff is lost to the air, this loss may be compensated for through nitrogen fixation by ***Azotobacter*** and other nitrogen-fixing bacteria when the ash is leached into the soil.

Annually burned loblolly pine stands in the lower coastal plain of South Carolina showed an increase in nitrogen of 23 kg/ha/yr (20.5 lb/acre/yr). Fixation rate in burned forest floor samples increased with moisture to above field capacity and with temperature from 25" to 35" C (77" to 95" F) (Jorgensen and **Wells** 1971).

From a study of microbial characteristics of a South Carolina forest soil after 20 years of prescribed burning, Jorgensen and Hodges (1970) found there were few indications that the burning adversely altered the composition of the saprophytic, sporeforming microfungi, or reduced the number of bacteria and actinomyces to the extent that soil metabolic processes were impaired.

Prescribed burning in a jack pine (*Pinus banksiana* Lamb.) stand on a sandy loam soil immediately decreased numbers and activity of most micro-organisms, but these increased abruptly after the first rainfall (Ahlgren and Ahlgren 1965). Depth and extent of burned area and the effects were influenced by intensity of fire and moisture conditions. Numbers and activity of organisms were generally lower the second growing season after burning, and some effects, especially a greatly increased *Streptomyces* population, were still evident the third growing season.

Greene (1935) found that 8 years of annual grass-burning under a longleaf pine *(Pinus palustris* Mill.) stand in Mississippi increased soil organic matter and nitrogen, originating chiefly from roots rather than from tops of plants. Growth of grass and leguminous plants on burned areas was more than twice that on unburned areas.

Pit burning, used where space and time are at a premium and residue pieces. are large, produces a hot fire and completely destroys all organic matter and micro-organisms in the immediate area. To replant the area, the pit must be filled in with fresh soil, preferably with topsoil piled aside during construction of the pit. Portable burning bins, used for smaller amounts of fuel, cause little damage to the soil.

Use of an air cushion logging raft (Anonymous 1972a) (tracked vehicle with directed high velocity air blower) instead of a bulldozer to push slash to a spot for burning would cause less disturbance of the soil. However, the air-blast would transfer more fine residues to the pile or pit. These finer organic particles could better be left on the soil as a mulch, both as a protection for seedlings and as an eventual source of nutrients.

Effects of burning on soil chemical and physical properties are discussed in detail by Moore and Norris (1974) and Rothacher and Lopushinsky (1974). Some examples of changes particularly important to microbial activity deserve mention. Burning of foliage, litter, and F-horizon material can result in loss into the atmosphere of a substantial portion of the nitrogen contained in forest floor material (Knight 1966). Obviously, the surface organic matter is also reduced. Soil pH and the carbon-to-nitrogen ratio can increase (Neal et al. 1965), and the mineral nutrients can be either redistributed or removed by leaching (Smith 1970). Soil bulk density can increase, and soil water-holding capacity and rate of moisture movement can decrease (Tarrant 1956, Neal et al. 1965).

The net effect of burning-induced changes on microbial activity has been studied in only a very few cases and is complicated by seasonal as well as long-term changes. Six months after Douglas-fir slash had been burned in Oregon, the numbers of soil bacteria were significantly greater than at an unburned site, but mold populations were reduced. Ammonium nitrogen also increased in soil of the burned site during this period (Neal et al. 1965). This may have resulted from partial sterilization which eliminated certain competitions or antagonists, and residual humus, perhaps thermally altered, became a suitable substrate. Some available carbon and nitrogen could have been contributed by rainfall and windblown organic matter.

Prescribed burning of a stand of jack pine in Minnesota resulted in an immediate decrease in numbers and activity of most micro-organisms, but these abruptly increased after the first rainfall. Some effects of burning on the soil microbiota were still evident in the third growing season after burning (Ahlgren and Ahlgren 1965). Too little is known about effects of burning and all the variables involved to generalize about either short-term or long-term effects on soil micro'bes. The net results, however, are not necessarily deleterious.

LEAVING RESIDUES UNBURNED

Decomposition of residues under forest conditions is particularly dependent on moisture, temperature, residue size, and an adequacy of available nitrogen. The closer each of these'approaches optimum, the faster will be the rate of decomposition and resultant nutrient cycling. From present knowledge, we assume the native micro-organisms will carry on their essential functions.

In standing forests, the rotting remains of earlier events could be left undisturbed to play their natural role in the ecosystem. Where concentrated, however, the remains could be crushed and scattered to distribute their nutrient potential and minimize undesirable effects.

By any method other than burning, natural disposal of forest residues left on the site will be slow, usually requiring many years. Methods for faster decomposition must be developed. To prolong the coincidence of moisture and temperature ranges most favorable to decomposition, the residue must be in close contact with or, preferably, embedded in the soil. Chipping, crushing, and burying are options where heavy equipment can be used. Chipping and crushing reduce particle size, important in attaining more rapid decomposition. Ideal is approximately 32- to 6-mesh screen size (equivalent to particle sizes of slightly less than 1/32 inch and 1/6 inch, respectively). The pieces should be blown or otherwise spread as uniformly as practicable over the ground and rolled, treaded, or churned to insure maximum contact with soil. Excessive compaction should be avoided. The layer of chips or crushed material should not be too deep; more than 6 inches could retard aeration of the lower strata and underlying duff or soil. A thinner layer allows more complete inoculation with decomposers distributed from dust or soil by wind and rain spatter.

Some chipped or crushed residues can be advantageously used as an erosion-retarding mulch on roadbanks or skidways.

BURYING

Disposal of slash, thinnings, and brush by burying may be feasible (Schinke and Dougherty 1966) where bulldozers could push the slash into pits about 10 to 12 feet wide, 50 to 100 feet long, and up to 10 feet deep (3 to 3.5 m wide, 15 to 30 m long, and up to 1 m deep), and then cover the slash with about a foot (30 cm) of soil. Enough soil for inoculation would be mixed with the "material during transfer and enough moisture would be held under the soil cover to allow fairly rapid decomposition. Addition of nitrogen fertilizer or establishment of dinitrogen-fixing plants would be desirable (Bollen 1969). Nitrogen must be added to avoid temporary nitrogen deficiency of tree regeneration if residue particles are incorporated into the soil (Cochran 1968). Depending on soil type, phosphate and sulfur fertilizers may be required.

Burying should not take place in heavy, poorly aerated soils or where there may be poor drainage and a high water table. In such cases, the material will ferment, decomposition will be incomplete, and acids and other undesirable end products will accumulate. Sufficient heat may be retained from the microbial and chemical reaction to cause spontaneous combustion and thus create a fire hazard (Bollen and Lu 1970).

Some compaction from use of equipment could be desirable to insure favorable contact with inocula and active surfaces, but repeated compaction over the same area could retard aeration. Some disturbance of the natural soil by any method involving heavy equipment is inevitable. As long as this is confined to the surface soil and does not admix much of the subsoil, the results should not be damaging.

OTHER USES OF RESIDUES

Availability of chips from residues offers potential for solving some of the other waste disposal problems of civilization. Application of sewage plant waste water to forest land has shown promise (Pennypacker et al. 1967). This involves functioning of the litter and F layer as biological and chemical filters and the long-term capability of the soil to act as a physical filter. Microbes decompose and metabolize biodegradable organic materials rapidly under favorable conditions of aeration and temperature; most of the sludge would be decomposed within a month if water relations were managed to avoid anaerobiosis, which would result in gas production, odor, and unsanitary conditions. Potentially toxic or ecologically undesirable compounds such as pesticides and phenols would be decomposed with sufficient residence time. Forest growth is promoted by water and nutrients from sewage plant effluents, and deer populations have increased in treated areas. Site and management are critical factors in obtaining good results.

After several years' study of sprinkler irrigation of sewage effluent in a mixed oak stand, a red pine *(Pinus* ***resinosa*** Ait.) plantation, and an old open field area planted with white spruce, Sopper and Kardos (1972) concluded that diversion of such waste water to the forest ecosystem should help to eliminate or alleviate many disposal and pollution problems. Secondary benefits observed were an increased recharge of ground-water reservoirs, increased growth of vegetation, and amelioration of unproductive sites. Detergent residues did not accumulate, suggesting complete degradation by soil micro-organisms. Extractable phosphate and exchangeable sodium increased in the sewage irrigated soil, but no other particular cation or group of cations appeared to be adsorbed or released. There were no significant qualitative or quantitative microbiological differences between the control and irrigated areas. Total nitrogen did not accumulate in the soil; apparently the effluent nitrogen was absorbed by the vegetation.

Biotoxic elements in compounds of heavy metals, including cadmium, copper, lead, nickel, and zinc, are present in sewage sludge in concentrations greater than in normal soils (Anonymous 1973) and may build up to undesirable concentrations from long-continued applications of sludge or, perhaps, even from waste water. A monitoring system to keep track of such metals thus added to soils and taken up by plants is desirable.

The Forest Service as well as the Corps of Engineers and several university experiment stations are involved in projects seeking feasible methods for the most efficient and beneficial methods for disposal and utilization of sewage plant waste.

A series of papers from a symposium on Recycling Treated Municipal Wastewater and Sludge through Forest and Cropland has recently been published. (Sopper and Kardos 1973). Topics covering waste water and sludge include chemical and biological quality; the soil as a physical, chemical, and biological filter; waste water quality changes during recycling; soil, vegetation, and other ecosystem responses; examples of operating and proposed systems; and research needs.

Bark or chips might be suitable for primary biological filters. Microbial decomposition would be enhanced by the addition of moisture and nutrients. Perishable garbage might also feasibly be disposed of in areas where residues can be chipped. A mix of residue, garbage, and soil, with added nitrogen when needed, would improve decomposition of both forest and city residues by increasing aeration and available nutrients. It would offer additional benefits of esthetics and odor suppression.

Agricultural uses of ground bark and wood residues should not be overlooked in localities where feasible (Bollen 1969), even though the current demand is supplied by sawmills and wood-processing plants.

MICROBIAL INTERACTIONS WITH CHEMICALS

Pesticides including herbicides, fire retardants, fertilizers, and petroleum products are all associated with production or treatment of forest residues. Any of these various chemicals are capable of destroying at least certain soil microbes under certain conditions, but this hazard is appreciable only when rates of application far exceed those generally used (Bollen 1961, Martin 1963).

PESTICIDES

Some of the pesticides, e.g., the chlorinated hydrocarbons, are quite resistant to microbial attack. Their deqradation by microbes and plant roots is slow (Mehendale et al. 1972), so that much can be leached or volatilized to become widely distributed in the biosphere. Others, such as the organic phosphates, are readily decomposed and may even stimulate microbial activity (Bollen et al. 1970, Bollen and Tu 1971). In general, the presence of most pesticides on forest residues is not likely to impede decomposition.

Similarly, residues produced by responsibly applied herbicides will likely be as readily decomposed by microbial attack as "natural" residues. To the extent they have been studied, organic herbicides have proven to be rapidly degraded and have little effect on microbial populations or activities (Bollen 1962, Norris 1966, Tu and Bollen 1969). Even arsenic compounds, such as cacodylic acid or monosodium methanearsonate (MSMA) used as silvicides in thinning operations, are degraded by soil organisms (Von Endt et al. 1968). Research in progress at the Forestry Sciences Laboratory, Corvallis, Oregon, indicates that these compounds applied at rates as high as 1,000 p/m arsenic equivalent have no appreciable effect on common forest soil microbes or on their general physiological activity in forest soil or litter.

Effects of pesticides on the forest ecosystem are more extensively discussed in this volume by Moore and Norris (1974).

FIRE RETARDANTS

Chemicals used in fire control operations now include diammonium phosphate, ammonium sulfate, and ammonium pyro (poly) phosphate (Handleman 1971). These have high fertilizer values of available nitrogen, and the phosphates also supply phosphorus. Sulfur from ammonium sulfate would be valuable on soils of humid regions and on soils derived from basalt because these are typically low in sulfate. Only when the concentration might be high enough to produce osmotic effects would these chemicals retard microbial action. However, such effects would disappear upon dilution by rainfall or snowmelt. Leaching from heavy concentrations could cause eutrophication in streams and lakes (Lotspeich and Mueller 1971). Aside from direct fertilizing value, the added nutrients would enhance desirable microbial action in the soil and on tree residues.

Other chemicals included in the retardant formulations include (1) thickeners, such as clays and gums; (2) corrosion inhibitors: (3) ferric oxide color; (4) stabilizers; and (5) flow conditioners. These are present in relatively minor concentrations and therefore would have very little effect on soil microbes.

Studies now in progress at the Forest Research Laboratory in Corvallis, Oregon, indicate that as much as 100 lb/100 ft^2 of Phos-Chek, a diammonium phosphate based fire retardant, has little effect on decomposition of organic matter and nitrification.

FERTILIZERS

Forest fertilization, especially with sources of nitrogen, commonly a limiting nutrient element in soils, is practiced to increase tree growth and to enhance early development of introduced native vegetation after fires. The need for fertilizers has been extensively discussed by Maki (1966). Aside from benefiting the plants, fertilizers promote microbial decomposition of forest residues and soil organic matter. Nitrogen fertilizers are subject to losses by leaching and by denitrification. Nitrate forms are subject to these losses directly; ammonium fertilizers and urea, only after nitrification.

Urea pellets, because of high nitrogen content (46 percent) and consequent lighter weight than ammonium sulfate or ammonium nitrate, are preferred for aerial application, usually at the rate of 200 pounds of nitrogen per acre (224 kg/ha). This is rapidly transformed to ammonium nitrogen (NH_4^+) by microbes in the soil, is then subject to assimilation by plant roots and microbes, or may be oxidized by nitrifying bacteria to nitrate (NO_3^-). Nitrate is generally not desirable because it is subject to leaching and to loss of nitrogen gases by denitrification. Whether or not NO_3^- may be a preferable form for assimilation by plants is questionable, but McFee and Stone (1968) found that Monterey pine (*Pinus radiata* D. Don) and white spruce seedlings exhibited greater growth and nitrogen uptake with an ammonium source than with nitrate. Ammonium is assimilated by most kinds of plants, the preference being determined by a combination of factors, including kind and age of plant, pH, assortment of other ions, and environmental factors (Prianishnikov 1942). The effect of forest fertilization on water quality has been discussed by Moore (1972). Total amounts of fertilizer nitrogen entering surface streams after aerial application of urea to forested watersheds were minor and below toxic levels.

Sulfur fertilizers are beneficial in humid regions where sulfate ($SO_4^{=}$) is readily leached, and also on soils derived from basalt, which is low in sulfur. Fertilizers carrying $SO_4^{=}$, as in ammonium sulfate ($(NH_4)_2SO_4$) or gypsum ($CaSO_4.2H_2O$), provide this nutrient. They could therefore promote decomposition and recycling of forest litter and residues. Pumice soils supporting stands of ponderosa pine have shown response to gypsum (Will and Youngberg 1972). Flour sulfur (S), preferably in pellet form for aerial application, becomes available after oxidation in the soil by *Thiobacillus thiooxidans* and related species. Phosphate fertilizers may be needed in some cases to supply available phosphate. Forest management operations that remove surface soil will seriously lower the N, P, and S status of the site, and the use of fertilizers will be essential.

PETROLEUM PRODUCTS

Hydrocarbon fuels, oil, grease dropped from mechanical equipment, and oil carriers of biocidal sprays are not likely to harm microbial decomposition of residues. About a hundred species of bacteria, yeasts, and molds, many indigenous to the soil, attack hydrocarbons, even those considered to be antiseptic (Zobell 1946, Jones and Edington 1968). Asphalt and rubber also are slowly attacked. Applications of crude oil to soil result in increased microbial populations and, in many cases, improve soil fertility.

CONCLUSIONS

RECOMMENDED PRACTICES

Any burning of forest residues results in immediate losses of nitrogen from the ecosystem. Hard burns can be deleterious to soil physical properties. Such adverse effects of burning can be avoided by taking advantage of present knowledge about soil microbes and their interactions with residues. Desirable microbial activity, including rapid decomposition of residues, gradual release of bound nitrogen and other nutrients for tree growth, and improvement of soil physical properties by humus development can be enhanced by proper treatment. Incorporation of rotted wood as well as leaves and comminuted thinnings and slash could improve aeration, drainage, and moisture retention properties. Such treatment entails (1) reducing residue particle size by chipping or crushing, (2) assuring good contact of residue particles with soil, and (3) fertilizing with nitrogen to overcome early nitrogen deficiency caused by rapid microbial population buildup. Because the nitrogen in residues and assimilated fertilizer is 'gradually released by death of microbial cells, relatively little is lost from the ecosystem. Technology now exists to conserve and increase fertility on many sites, although better, more economical methods can doubtless be devised. The long-term potential benefits of improved site productivity must be kept in mind when costs of the treatment are reckoned. Residue and fertilizer treatments can be designed to serve as site preparation for regeneration as well. Forests, if not abused, tend to improve fertility of the soil, especially if use can be made of soil-ameliorating trees such as alder (*Alnus* spp.) and black locust (*Robinia pseudoacacia* L.).

RESEARCH NEEDED

So little research on soil microbial relationships of forest soils has been done that virtually all aspects need further work. High priority needs in relation to residues and residue treatments include (1) research techniques; (2) evaluation of long-term as well as short-term effects of treatments; (3) development of more economical and more widely applicable methods to hasten residue decomposition; (4) studies on specific situations, including combinaations of tree species, climate, soil type, and residue; (5) more efficient methods of evaluating effects of residue treatments on microbial activity--existing methology may serve the purpose, but it needs to be better adapted for easy field use, and the interpretive value for results needs to be confirmed; (6) soil respiration determinations for evaluating effects of different residue treatments on microbial activity; (7) studies on long-term effects--the short-term effects of some residue treatments on nitrogen cycling in ecosystems have been studied to some degree. Microbial decomposition of residues is an integral feature of the cycling process, controlling the rates and times of nitrogen release. We must learn how the process is influenced by varying the major factors that affect microbial activity before we can quantitatively predict long-term effects of residue treatments. Long-term effects must be reasonably predictable in order to compare the net benefits of treatment alternatives.

More effective and efficient means of hastening microbial decomposition of residues and nitrogen recycling probably can be developed--certainly few have been tried to date. Nitrogen-fixing plants such as legumes, alder, and ceanothus have been effectively used in forests in lieu of nitrogen fertilization. These nitrogen fixers offer many benefits in terms of enhanced microbial activity, residue decomposition, and continuing nitrogen input (Tarrant and Trappe 1971). At the same time, they present silvicultural problems that need to be overcome. (8) studies of nitrification inhibitors. Outflow of nitrogen from ecosystems could conceivably be stemmed by applications of nitrification inhibitors and more strategic placement of residue fragments. The potential of multiple benefits from use of fragmented residues in sewage waste water and garbage disposal on forest land should be explored. (9) evaluation of differential response to ammonium fertilizers of different tree species in different situations, including deficiency of other nutrients, to obtain maximum response from nitrogen sources. In this connection the possible value of nitrification inhibitors should be investigated. (10) working out the technology of sewage waste water and garbage disposal, evaluating first the microbiological and other ecosystematic factors.

EQUIPMENT DEVELOPMENT

Equipment that combines fragmentation of residue and scattering or mixing with soil, nitrogen fertilization, and possibly even seed broadcasting into a single operation could substantially increase efficiency of residue treatment. Development of such equipment and also equipment for fragmenting residues on steep slopes should receive high priority.

RELATED INVESTIGATIONS IN PROGRESS

1. At the Forestry Sciences Laboratory, Corvallis, Oregon.

Effect of fire retardants on microbial activities in forest litter and soil, with emphasis on organic matter decomposition and nitrification. W.B. Bollen.

Decomposition of litter in different forest stands. Kermit Cromack, Jr.

2, In the Coniferous Forest Biome. Ecosystem Analysis, International Biological Program. 1973-1974.

Decomposers on living twigs and foliage. G.C. Carroll, C. Driver.

Decomposer process studies. W.C. Denison, G.C. Carroll.

Further studies ,on the characterization of primary decomposition of the wood components of the Douglas-fir ecosystem. D.H. Driver, W.C. Denison.

Energy flow as determined by rates of litter decomposition. C.M. Gilmour, C.T. Youngberg.

A coordinated study of movement of elements from vegetation to soil in coniferous ecosystems. C.C. Grier.

Role of microfauna in biogeochemical cycling. H.J. Jensen, G.W. Krantz.

Coordinated nutrient cycling and litter decomposition study. **D.P.** Lavender, W.C. Denison, J.R. Sedell.

Fixation, uptake, and release of nitrogen by epiphytes. L.H. Pike.

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SOIL PROCESSES AND INTRODUCED CHEMICALS

Duane G. Moore and Logan A. Norris

ABSTRACT

Forest residue management is not likely to have a short-term influence on soiZ formation unless significant surface erosion or soiZ mass movements occur. Long-tern changes in the rate and direction of soiZ formation may result from intensified management practices including residue treatment. Measurement of these changes is difficult because of the Zong period of time required for soiZ formation. Clearcutting and severe burning temporarily interrupt or reduce nutrient cycling, but normal cycling is restored as revegetation occurs. All types of burning result in loss of some nitrogen. The portion of nitrogen capital Zost depends on the amount and kind of residue burned and the completeness of combustion. Availability of other nutrients is increased temporarily after burning, and some recovery of nitrogen may occur through increased nitrogen fixation. Disposal of coarse woody residues by pile or pit burning results in Zoss of nitrogen from the site, but other nutrients remain. Mechanical treatment and spreading of residues increase the rate of both residue decomposition and nutrient reZeasa, but availability of native nitrogen may become Zimiting and the addition of fertilizer nitrogen necessary. Fertilizer and fire retardant chemicals increase the nutrient content of residues and may influence the seZection of residue treatment methods. Forest residues and residue treatments may influence pesticide distribution and persistence to a small degree, but the opportunity for interaction is Zimited by the timing of residue treatment and pesticide appZications.

Keywords: Soil chemical processes — nutrient cycling, fertilizers, pesticides, fire retardants; soi1 formation.

INTRODUCTION

Forest residues, whether natural or resulting from the influence of man, play an important and necessary role in soil-forming processes and in maintaining the productivity of forest soils. Treatments which remove or disturb the organic layers can greatly modify the dominant physical and chemical reactions operating in the soil and thereby change the conditions which influence soil development and nutrient availability. Complete removal or destruction of surface residues will change soil physical properties and, at least temporarily, will destroy one of the primary links in the nutrient cycle. However, treatments that result in only partial removal (for fire protection) or less severe disturbance may have little effect on soil conditions and may even result in increased nutrient availability. Residue management practices must be consistent with maintenance of soil physical properties and conservation of plant nutrients. They must also meet the needs for fire protection and rapid reforestation. Development of appropriate treatments is complicated by wide variations in amounts of residues, natural and manmade, associated with differences in forest type, climate, and topography.

Forest residue is defined by Jemison and Lowden (1974) as the dead, standing, or down woody material that accumulates over time on the forest floor. Unwanted brush and unusable tree parts left after a harvesting operation are also included. Forest floor is a broad term and is defined by the Soil Science Society of America Committee on Terminology (1965) as "All dead vegetable or organic matter, including litter and unincorporated humus, on the mineral soil surface under forest vegetation." "Forest residue" and "forest floor" are used in the following sections with the above definitions. Other soil science terms are used as defined by the SSSA Committee on Terminology. In this paper we discuss the effects of residues and various kinds of residue treatments on soil processes--including soil formation and nutrient capital, availability, and cycling--and on the many introduced chemicals used in forest management.

SOIL PROCESSES

Management of forest residues may have a direct effect on several important soil processes. Effects on soil microbiota, soil stability, and water yield and quality are discussed in other chapters of this Compendium. Processes covered in this section are soil formation and nutrient cycling.

Characteristic physical and chemical properties of forest soils are dependent on more or less continuous forest cover. Because the soil remains relatively undisturbed, well-defined organic layers can develop on the soil surface, and the forest vegetation can exert a strong influence on soil development. Nutrition of forests is the result of their efficient use of the nutrients released by decomposition of accumulated organic residues. Residue management which alters these characteristics of the forest soil has the potential to influence both soil formation and nutrient cycling.

SOIL FORMATION

Soil development is the process of changing parent materials into soil through the integrated action of various environmental forces. The soils produced have more or less definite physical, chemical, and biological properties depending on the relative influence of parent material, climate, living organisms (including surface vegetation), topography, and time. As development progresses, these properties, continue to change and usually become more distinct. Maintenance of characteristic properties of forest soils is dependent on the presence of layers of partially to completely decomposed organic material on the soil surface and the continuous or periodic addition of fresh material as litter fall. Detailed information on soil formation processes is available (Lutz and Chandler 1946, Forest Soils Committee of the Douglas-fir Region 1957).

Transformation of parent material into well-developed forest soils is a long-term geologic process. Residue management is, therefore, unlikely to result in any short-term effects on soil formation. One possible exception is a residue treatment that increases the likelihood of slides or other major disturbances that could interrupt the soil development process.

Although more difficult to identify and control, long-term impacts of residue management practices on soil formation are possible. Changes in land use, such as converting forest land to production of agricultural crops, result in marked changes in many soil processes. Residue management as a part of intensified forest resource management constitutes, at least a modification in land use. To the extent that these programs result in a change in the rate of addition of organic material to the forest floor, they can result in gradual long-term changes in the rate or direction of soil formation processes. Whether these changes will significantly alter the productivity of forest soils is unknown and deserves study.

NUTRIENT CYCLING

Forest ecosystems are dynamic communities characterized by a large and highly efficient internal circulation of nutrients between plant cover and soil. Production of large quantities of biomass from relatively infertile soils is a result of the efficiency of this cycling system, and rapid nutrient release through decomposition of accumulated forest residues is an essential part of the cycle. Total capital and availability of accumulated nutrients are a function of the combined effects of forest type, parent material, soil, and climate.

Cycling of plant nutrients begins with the establishment of vegetation, and the kind and quantity of nutrients cycled change as the ecosystem passes through various phases of forest succession. Mineral and organic nutrients come from three sources: geological weathering of parent material, meteorological inputs, and biological inputs including the activities of man (Cooper 1969). In undisturbed forests, the main nutrient losses are via volatilization to the atmosphere, soil erosion, and leaching of dissolved chemicals. Managed forests are subject to additional losses resulting from timber harvest and residue removal or treatment. Maintenance of site productivity depends on balancing output against input. Nutrient cycling in forest ecosystems has been the subject of several papers (Cole et al. 1967, Cooper 1969, Fredriksen 1972, Likens et al. 1970, Ovington 1965, Switzer and Nelson 1972, Weetman 1961).

Nutrient Capital

Interest in nutrient balance under forest stands and recognition of the relationship between accumulated residues and site productivity developed more than a century ago (Zinke 1969). However, early studies were primarily concerned with the composition of forest floor materials; the ecosystem concept of nutrient cycling did not develop until recent years. Data on total nutrient capital are still meager because of severe sampling problems caused by extreme variability in forest floor and soil materials on and between similar forest sites (Grier and McColl 1971).

Tarrant et al. (1951) demonstrated marked differences in annual litter fall and nutrient content between 10 major species of the region. Western redcedar (*Thuja plicata* Donn) and old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb) Franco) contributed the largest amounts of fresh litter, but red alder (*Alnus rubra* Bong.) foliage contained nearly three times the amount of nitrogen (28 lb/acre--31.4 kg/ha) as the average of the other species. Phosphorus content of foliage was relatively low for all species reflecting the characteristically low phosphorus availability of highly acid forest soils. Bigleaf maple (*Acer macrophyllum* Pursh) and red alder contained high amounts of potassium compared with the conifers, and western redcedar and bigleaf maple foliage samples were the only ones containing more than 1 percent calcium. Ponderosa (*Pinus ponderosa* Laws.) and lodgepole pines (*Pinus contorta* Dougl.) were at the bottom of the list for both nutrient content and annual fall of litter.

Several investigators have studied the accumulation of forest floors and their nutrient composition under northwestern coniferous forests (table 1). Weights of total accumulation in these studies ranged from 16,230 to 199,095 lb/acre (18,190 to 223,146 kg/ha). Greatest variation occurred under mixed conifer stands in eastern Washington. Much of the variation in total weights was attributed to the frequent occurrence of forest fires throughout most timber types. A narrower range of variation occurred in western Oregon (20,000 to 76,000 lb/acre) (22,400 to 85,180 kg/ha), and on these sites, differences could be correlated with the presence of various types of understory plant communities.

Nutrient content in the forest floor also varied considerably in every study, but in most instances the largest amounts were associated with the greatest accumulations of organic material. Lowest amounts of nitrogen were reported for a 30-year-old stand of Douglas-fir on a severely burned area (Tarrant and Miller 1963). Amounts of available phosphorus were consistently low on all sites, and they represented from 5 to 10 percent of the total weight of phosphorus. Both weight and concentration of potassium were usually higher in central Washington than in other regions.

Only three studies report data on the amount of nutrients in the underlying mineral soils (table 2). Under young stands such as that studied by Cole et al. (1967), 85 percent of the total nitrogen budget is present in the soil, 5 percent in the forest floor, and 10 percent in the standing vegetation. Red alder increased the accumulation of nitrogen in soils under pure and mixed stands, and Douglas-fir greatly increased the amount of exchangeable calcium (Franklin et al. 1968). Available phosphorus is very low and represents only an extremely small fraction of the total present; from 95 to 98 percent of this nutrient is in the soil. Amounts of total potassium and calcium are not reported, but the largest portion of these nutrients is also found in the soil component of the ecosystem.

Distribution of organic matter, nitrogen, phosphorus, potassium, and calcium in the various components of a second-growth Douglas-fir ecosystem is presented in table 3 (from Cole et al. 1967). Nutrient content of the forest floor and surface layers of mineral soil illustrates the importance of these components in the nutrient cycle. Subordinate vegetation contained only small amounts of nutrients but may play an important role on some sites. Comparable data for old-growth stands are not available. However, rough approximations can be made for older stands by assuming that (1) foliar mass and forest floor remain relatively constant once litter fall is balanced by rate of decomposition and (2) increases in nutrient content of the standing crop are proportional to increases in volume of woody tissue.

Table 1.--*Average total weight and nutrient content of the forest floor under coniferous forests in Washington and Oregon*

Region	Forest type	Accumulation of forest floor	N	P	K
		- - - - - *Pounds per acre* - - - - -			
Central Washington[1]	Mixed conifers	63,820	571	74	236
Western Washington[2]	Old-growth mixed conifers	140,864	1,820	127	113
	Young Douglas-fir	25,465	292	26	37
Eastern Washington[2]	Young Douglas-fir	12,760	172	14	13
Southwest Washington[3]	Young Douglas-fir	24,535	141	--	
Ore'gon Coast Ranges[4]	Young Douglas-fir	34,460	347	47	57
Cascade Range, Oregon and Washington[5]	True fir-hemlock	56,754	581	[6] 4	[7] 54

1/ Wooldridge (1970).

2/ Gessel and Balci (1965).

3/ Tarrant and Miller (1963).

4/ Youngberg (1966).

5/ Williams and Dyrness (1967).

6/ Available phosphorus.

7/ Exchangeable potassium.

Table 2.--*Nutrient capital in the soil under various forest types in Oregon and Washington*

(In pounds per acre)

Forest type	Total N	Available P	Exchangeable K	Exchangeable Ca
True fir-hemlock[1]	7,895	28	467	891
Douglas-fir[2]	2,506	[3]3,460	209	661
Douglas-fir[4]	11,720	8	920	1,123
Red alder[4]	16,680	7	1,167	324
Alder-conifer[4]	12,640	5	805	246

1/ Williams and Dyrness (1967).

2/ Cole et al. (1967).

3/ Total phosphorus.

4/ Franklin et al. (1968).

Table 3.--*Distribution* of *N, P, K,* Ca, *and* organic **matter in** a 35-year-OM **second-growth** *Douglas-fir* **ecosystem**[1]

(In pounds per acre)

Component	N	P.	K	Ca	Organic matter
Tree:					
Foliage	91	26	55	65	8,116
Branches	54	11	34	95	19,656
Wood	69	8	46	42	108,569
Bark	43	9	39	62	16,709
Roots	29	5	22	33	29,430
Total	286	59	196	297	182,480
(Total, kg/ha)	(320)	(66)	(220)	(333)	(204,524)
Subordinate vegetation	5	1	6	8	901
Forest Floor:					
Branches	4	1	4	7	1,270
Needles	31	4	4	24	2,681
Wood	13	2	7	15	5,661
Humus	108	17	13	76	10,706
Total	156	24	28	122	20,318
(Total, kg/ha)	(175)	(27)	(31)	(137)	(22,772)
Soil (depth):					
0- to 6-inch	722	1,042	71	279	34,236
6- to 12-inch	774	1,066	59	175	32,954
12- to 18-inch	679	874	46	136	25,240
18- to 24-inch	331	478	33	71	7,097
Total	2,506	3,460	[2]209	[2]661	99,527
(Total, kg/ha)	(2,809)	(3,878)	(234)	(741)	(111,550)
Total ecosystem	2,953	3,544	439	1,088	303,226
(Total, kg/ha)	(3,310)	(3,972)	(492')	(1,219)	(339,856)

1/ Based on data from Cole et al. (1967).

2/ Exchangeable amounts only for K and Ca in soil.

Nutrient Availability

Varying quantities of litter fall are added to the forest floor annually; and over a period of years in some areas, large amounts accumulate. Nutrient minerals are a significant part of these accumulations; and unless released to circulate, a substantial part of the nutrient capital of the ecosystem will eventually be stored in the forest floor. Cole et al. (1967) found that in a 35-year-old, second-growth Douglas-fir ecosystem the current annual uptake of N, P, K, and Ca was 35, 6, 26, and 22 lb/acre (39, 7, 29, and 25 kg/ha), respectively (table 4). During the same year, amounts of nutrients equivalent to approximately 40 percent of the annual uptake of N, 14 percent of the P, 55 percent of the K, and 80 percent of the Ca were returned to the forest floor as litter. Also, of the nutrient inputs to the forest floor, Cole et al. found that amounts equivalent to about 31 percent of the N, 100 percent of the P, 60 percent of the K, and 90 percent of the Ca were leached from the forest floor and returned to the soil. With the amounts of nutrient input from precipitation added to the above data, net rates of accumulation of N, P, K, and Ca in the forest floor were 11, 0, 5, and 1 lb/acre/yr (12, 0, 6, and 1 kg/ha/yr). Thus, the forest floor acts as an important reservoir for that part of the total nutrient capital actively cycled through the ecosystem.

Table 4.--*Annual transfer of nitrogen, phosphorus, potassium, and calcium between components of the ecosystem*[1]

(In pounds per acre)

Transfer	N	P	K	Ca
Uptake by forest	35	6	26	22
Returned to forest floor[2]	15	1	14	17
Leached from forest floor	4	1	9	16
Net gain to forest floor	11	0	5	1
Leached beyond rooting zone	1	0	1	4

1/ Based on data from Cole et al. (1967).

2/ Includes nutrient input in precipitation.

In the above system, K is cycled more rapidly than Ca, followed by N, and then P. Transfer rates among components of the ecosystem depend on the properties of each nutrient and how it is used by the plant. The proportion of nutrients in the litter layer is determined by their distribution within the tree and the makeup of the litter, i.e., the relative amounts of leaves, twigs, branches, bark, and bole wood. In general, the largest quantities of the essential elements' are present in the foliage, but the highest percentage concentration of Ca is often found in the bark. Both absolute quantities and concentrations of N, P, K, and Ca are dramatically different among species of the same age (Curlin 1970). Nutrient return to the forest floor is largely through litter fall, but on humid sites foliar leaching may also be important.

Once on the forest floor, litter is immediately subject to attack by large populations of micro-organisms, and initial decomposition of the finer components is quite rapid (Bollen 1974). Residues are subject to intensified leaching and may also be utilized by various groups of microfaunal population. As the more easily decomposed materials are mineralized, the rate of activity slows down but continues for several months to several years. Decomposition rates of litter from different forest types depend on the carbon-to-nitrogen ratio, mineral content, microbial inhibitors, and physical properties such as particle size. Climatic factors such as temperature level and moisture availability regulate the rate of the decomposition process and determine whether accumulation exceeds or is in equilibrium with the rate of decomposition.

With the exception of nutrients that are susceptible to leaching from living or dead plant materials, nutrient release depends on the mineralization process.1/ Potassium and phosphorus apparently remain in readily soluble forms in leaf litter and are almost immediately leached into the soil (Curlin 1970, Cole et al. 1967). Calcium is a constituent of cell walls, and nitrogen is tied up in insoluble proteins and other complex organic compounds. Thus, these nutrients are not as rapidly released. Once those nutrients subject to rapid leaching are removed, subsequent nutrient release will be at a rate proportional to carbon release and weight loss.

Part of the nutrients released through decomposition is leached into the mineral soil along with soluble organic colloids. A significant fraction., however, is retained in the forest floor by adsorption onto the substrate, bonding to exchange sites, or reincorporation into the organic component through microbial utilization. Wells and Davey (1966) reported that the forest floor may have a higher capacity to retain cations than several inches of the underlying mineral soil , especially coarse-textured sandy forest soils. They also found that, regardless of the kind of litter or its state of decomposition, the cation-exchange capacity is highly correlated with the nitrogen content. The surface layers of mineral soil also have a high content of organic matter, and the combined effect of these layers helps to explain the apparent nutrient conserving characteristics of the forest soils. Thus, the importance of maintaining the organic matter content both on and in the soil is clear.

The availability of nitrogen in forest soils is of particular interest since it is the nutrient most often limiting maximum growth. Accumulated

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1/ Mineralization is the conversion of an element from organic to an inorganic state as a result of microbial decomposition.

organic matter may contain large quantities of nitrogen that are unavailable to plants. Tamm and Pettersson (1969) found the organic residues of the B horizon were highly resistant to mineralization. Organic matter in the A horizon was less resistant, but release of nitrogen was still quite slow. When C^{14} dating techniques were used to determine the age of the humus fractions (Tamm and Holmen 1967), ages obtained for the B horizon varied from 330-465± 65 years. This work emphasized the importance of the surface organic layer in particular, and the A horizon to less extent, for nitrogen nutrition on podzol and related soils.

Clearcutting temporarily stops the normal circulation of nutrients between plant cover and soil system until the area is at least partially revegetated. Maximum increases in mean temperatures and available moisture can be expected to favor rapid decomposition of accumulated residues and increase nutrient release to the soil. Removal of the canopy also interrupts the evapotranspiration cycle and increases the amount of water moving through the soil system. Leaching of mineralized nutrients is increased, but many forest soils have a high capacity to retain these nutrients against loss to ground water or surface streams (Cole and Gessel 1965, Fredriksen 1972). Revegetation also usually occurs rapidly; and within a few years, conditions on the site approach the steady-state cycling systems characteristic of the area prior to harvest (Marks and Bormann 1972). Partial cutting by shelterwood harvest and various thinning and pruning operations have less effect on nutrient cycling depending upon the amount of residues returned to the forest floor. In each instance, amount and distribution of slash and extent of disturbance of the forest floor and soil are further influenced by the logging method used.

Impacts of Residue Management

Nutrition of forest ecosystems is a primary concern of forest land managers. Few studies have examined specific effects of residues and residue treatments on nutrient cycling with the exception of the effects of burning. However, there is extensive literature on nutrient capital and nutrient cycling in forests which can be related to the present discussion.

Manmade Residues

Effects of residues on nutrient availability and cycling vary with the age of stand harvested, proportion of unmerchantable timber, and distribution of slash over the disturbed area. In young stands, a higher proportion of the slash is made up of foliage and smaller diameter branches. Residues from old-growth stands contain a larger component of heavy woody material which is not as readily attacked by decomposing organisms. Nutrient content varies with differences in species composition and is higher in the foliage component.

Release of nutrients through microbial decomposition of the newly added slash and the already present natural residue is dependent on moisture, temperature, aeration, particle size, contact with the soil, and an adequate supply of available nitrogen. Organisms able to attack the water-soluble constituents of fresh residues multiply rapidly and assimilate much of the available nitrogen. Foliage, twigs, and smaller branches have a relatively high nitrogen content, and decomposition usually proceeds rapidly under favorable conditions of moisture and temperature. Coarse woody residues make up a much larger proportion of the total residue volume and also have a low nitrogen content. Sawmill residues such as bark and sawdust have a similar wide ratio of carbon to nitrogen content, and decomposition of these low nitrogen residues is very slow without some form of treatment. Interactions between soil microbes and forest residues are discussed in more detail elsewhere (Bollen 1974, Aho 1974).

Residue Treatments

Any harvesting or cultural practice, including various residue treatments, that greatly disturbs the original forest floor layers and underlying soil may result in at least a temporary change in the availability and rate of cycling of nutrient elements. Removal of the forest floor reduces the capacity of the site to retain released or added nutrients.

No treatment.--Decomposition of untreated coarse residues may require several years. Therefore, some form of treatment is needed on most sites to hasten the rate of mineralization and the recycling of nutrients. Thinning and partial harvests in young-growth stands and harvesting of individual selected trees in older stands leave less residue which is usually well distributed over the site and contains a higher proportion of fine slash. Residues of this kind will readily decompose, similar to natural litter fall, and treatment may not be necessary.

Rearrange and leave.--Rearrangement of large accumulations of natural residue and logging slash to create working space for reforestation and fire control depends on the logging method used. Cat logging produces a network of skid trails; and coarse residues, along with part of the finer components, are concentrated in piles or windrows. Hi-lead logging leaves much of the natural residue and lighter slash distributed over the unit but tends to concentrate cull logs and debris near the landing: Yarding unutilized material (YUM) concentrates huge piles of residue at one or more locations. Aerial logging systems generally leave the logging slash evenly distributed over the unit, but later rearrangement may be necessary to provide access. Disturbance of the forest floor and soil is obviously greatest for surface logging systems.

Nutrient capital contained in collected residues is concentrated on a small portion of the total area and will be recycled only very slowly. Smaller piles and windrows containing a higher proportion of lighter slash intermixed with soil will decompose in a few years. Accumulations of cull logs provide poor moisture-temperature relationships for microbial activity and will not decompose for many years. However, these piles of coarse residue contain only a small percentage of the total nutrient capital. Availability of nutrients for rapid regeneration will not be greatly altered on those parts of the unit subjected to little disturbance of the forest floor and soil. Restoration of normal nutrient cycling on skid trails can be hastened by seeding and covering areas of exposed mineral soil with light slash.

Treat *mechanically and leave*.--Portable chipping or chunking equipment can be used to reduce the particle size of accumulations of coarse branch and stem material. Redistributing the chips over the soil surface will speed their decomposition and protect disturbed areas at the same time. However, the low nitrogen content of these components may necessitate the addition of fertilizer nitrogen to enhance microbial activity and prevent depletion of available nitrogen even on sites of relatively high native fertility. From data for soils of central Oregon, Cochran (1968) concluded that spreading chipped thinning slash over the surface of pumice soils would not reduce nitrogen availability. Should the chipped slash be mechanically incorporated into the soil, however, a temporary nitrogen deficiency would be likely; and this effect would be more pronounced on finer textured nonpumice soils. More intimate contact between residue and soil increases the rate of microbial activity resulting in increased immobilization of nitrogen, but the deficiency can be replaced by small additions of fertilizer.

Spreading of residues on steep or otherwise unstable slopes should be carried out from existing road systems to the extent possible rather than creating further disturbance. Crushing and burying are other possible treatments where heavy equipment can be used. Crushing tends to reduce particle size and also increases contact with soil, thus speeding up decomposition and nutrient release. Excessive compaction or too great a depth of the crushed layer may retard aeration and decomposition. Burying may be feasible for disposing of large accumulations of coarse logging residue or brush; heavy disturbance of forest floor and soil will be restricted to the area around the pits. Nutrients contained in the residues will not be lost but will be concentrated in a small area rather than evenly distributed over the entire unit. Bollen (1974) discusses other precautions to insure fairly rapid decomposition without undesirable products.

Burn.--Disposal of forest residues and logging slash by burning is perhaps the most controversial choice of currently used treatment methods because of the potential for detrimental impact on nutrient cycling and site productivity. The fate of organic matter and nitrogen is of primary interest because of their importance to soil physical properties and nutrient release. Severe burns, such as those caused by wildfire or piled burning, can result in nearly complete destruction of organic matter and cause changes in the physical, chemical, and biological properties of the upper layers of mineral soil (Neal et al. 1965). If combustion of organic matter is complete, all contained nitrogen is lost to the atmosphere. Oxidation is usually incomplete, however, and the extent of nitrogen loss is proportional to the intensity of the burn and the kind of fuel consumed. Broadcast burning removes much of the fresh surface litter and light slash which contain most of the nitrogen in the residues. Burning of coarse residues (wood and bark) in piles or pits would result in smaller losses by leaving most of the high nutrient materials on the site.

Cooper (1971), Stone (1971), and Wells (1971) presented the effects of burning on nutrient availability at a symposium. Periodic prescribed underburning reduced the amounts of organic matter on the surface, but the organic matter content of the surface layers of soil (0- to 2-inch (0- to 5-cm) depth) increased by up to 30 percent. The principal effect of burning was a redistribution, not a reduction, of organic matter in the profile (Wells 1971). Reduction in the amount of surface residue was accompanied by a decrease in the total amounts of P, K, Ca, and Mg in the forest floor, and these nutrients were carried into the mineral soil where available phosphorus and exchangeable K, Ca, and Mg increased.

Under periodic prescribed burning as practiced in the Southeast, most of the yearly addition of nitrogen in litter is volatilized by fire (Stone 1971). However, after 20 annual burns, the nitrogen content lost from the forest floor was compensated for by an approximately equal increase in nitrogen in the surface layer of mineral soil. The increases in soil nitrogen were attributed to increased rates of nitrogen fixation brought about by an increase in pH (Wells 1971, Stone 1971). Overall conclusions from several studies were that prescribed burning had no deleterious effects on chemical or physical soil properties and did not decrease soil productivity. Controlled use of fire in the Pacific Northwest is not carried out under strictly comparable conditions of residue situations and climate, but the conclusions reached may apply generally.

Numerous studies on the effects of slash burning on chemical, physical, and microbial properties of forest soils have been conducted in the Douglas-fir region (Neal et al. 1965, Tarrant 1956, Tarrant and Wright 1955, Dyrness 1963, Dyrness and Youngberg 1957, Morris 1970). Conflicting results obtained under different conditions have contributed to the controversy surrounding the effects of burning. Many of the differences can be explained by wide variations in the intensity of burning and the relative properties of lightly burned, severely burned, and unburned areas. In general, burning increases the amounts of available nutrients in the surface soil with the possible exception of nitrogen. Some studies report significant nitrogen loss, but others report small losses or no effect. Loss of nitrogen and release of other nutrients are associated with a decrease in organic matter content of the forest floor. On severely burned sites, organic matter content of the soil may also be reduced. Detrimental effects on soil physical properties are confined to severely burned areas, and a number of studies have shown that only 3 to 8 percent of the total area is severely burned over a typical broadcast slash burn (Tarrant 1956, Dyrness and Youngberg 1957). Soil pH of the surface layers is increased due to the increased content of exchangeable bases.

Clearcutting old-growth Douglas-fir stands leaves large accumulations of slash and coarse residues. Dell and Ward (1971) reported weights of coarse residues ranging from 32 to 227 tons/acre (72 to 509 metric tons/ha) on clearcut units of western Oregon and Washington. The finer materials, including foliage, twigs, and small branches, make up a smaller portion (20 to 40 tons/acre--45 to 90 metric tons/ha) of the total weight; but these materials contain a large proportion of the nutrient capital and are more rapidly decomposed than wood and bark. Coarse woody residues will not decompose for many years if not salvaged, chipped, or burned. YUM or some other method of piling the coarse residues will permit their disposal by burning while leaving most of the lighter slash, with its higher nutrient content, distributed over the unit. Burning piled residues produces a hot fire which may completely destroy the organic matter, including the forest floor beneath the pile. However, the effects of burning are restricted to a small area. Forest floor destruction and soil damage from pile burning can be minimized by moving the litter and topsoil to one side before piling. Similar precautions can be taken before digging a burning pit. After residue treatment, topsoil and forest floor material can be spread over the surface of the pile-burn site and over the filled pit.

Most of the nitrogen contained in the residue is lost during disposal by piled burning, and all nitrogen is lost during pit burning because of the hotter fire and more complete combustion. Most of the sulfur and boron will also be lost, but other nutrients will remain in the ash. Amount of nitrogen lost will, of course, depend on the volume of residue burned, the proportions of bark and wood, and the concentration of nitrogen in each material. An estimate of the distribution of biomass and nitrogen in an old-growth Douglas-fir stand is given in table 5. The information is based on average nitrogen concentrations and estimated distributions of biomass for a hypothetical 400-year-old, site class III, stand of Douglas-fir yielding 19,300 ft^3 (547 m^3) of merchantable wood per acre (hectare). With a proportion of 85-percent wood and 15-percent bark with nitrogen concentrations of 0.04 percent and 0.10 percent, respectively, an accumulation of 100 tons (90.7 metric tons) of cull logs would contain approximately 100 pounds (45 kg) of nitrogen. Since the nitrogen contained in this kind of residue would be recycled only very slowly if left on the harvesting unit, removal by burning would not have a significant effect on amount of nitrogen available for reforestation. On sites which have a low nitrogen capital (less than 3,000 lb/acre--3,362 kg/ha), however, burning could result in losses of up to 5 percent or more of the total. Broadcast burning would consume most of the light slash and at least parts of the coarse residue and forest floor resulting in a loss of 300 to 500 pounds of nitrogen per acre (336 to 560 kg/ha), even more if conditions are quite dry. This loss would have a significant impact on nitrogen available for the next crop.

Table 5.--*Approximate distribution of biomass and nitrogen in a 400-year-old stand of Douglas-fir, site class III*[1/]

Component	Biomass	Nitrogen	
	Tons per acre	*Pounds per acre*	*Percent of total*
Removed by harvest	328	321	4.4
Unmerchantable residue	142	139	1.9
Fire slash (4-inch pieces)	30	300	4.1
Forest floor	30	600	8.1
Soil (to 36-inch depth)	--	6,000	81.5
Total	--	7,360	--
(Total, kg/ha)		(8,249)	

1/ Data based on a hypothetical old-growth stand developed from published yield tables and several references on distribution of biomass and nutrient capital.

Nutrients released by broadcast burning may accumulate in lower layers of the forest floor or move into the mineral soil. Increases in nutrient availability for cycling and utilization, however, may also increase nutrient vulnerability to loss by leaching. Grier and Cole (1971) found slash burning caused substantial increases in the concentrations of nutrient ions entering the soil. Downward movement was also increased, but most of the nutrients were retained in the surface 15 inches of soil, and only insignificant amounts were leached from the rooting zone of the profile. Nutrients contained in the ash from piled and pit burning will be concentrated in small areas, and the capacity of the soil to adsorb and hold these elements may be exceeded. Collected nutrients will be better utilized and the chance of loss by leaching into surface or ground water will be reduced if the ash is spread over a larger area.

Exclusion of fire from forests where rate of litter fall exceeds the rate of decomposition has resulted in gradual accumulation of residues. These accumulations may constitute a fire hazard and also represent removal of large amounts of nutrients from active circulation. Periodic light underburning may be used to reduce the hazard and also reduce the competition from subvegetation. Most of the nitrogen contained in the burned residue is lost to the air, but the availability of other nutrients is increased as the ash is leached into the soil. Increased nutrient availability from the ash has been shown to stimulate nitrogen fixation following prescribed burning in other regions (Jorgensen and Wells 1971), thus compensating for the loss, but comparable information is not available for the Northwest. Prescribed underburning in ponderosa pine forests east of the Cascades may be possible without detrimental effects on nutrient cycling.

Removal of residues.--Removal of coarse residues for utilization or disposal will remove nutrients which would otherwise eventually reenter the nutrient cycle. However, because the nutrients contained in the coarse residues represent a small fraction of the total capital, and natural decomposition of woody residues is very slow, the impact on nutrition of the next crop would be minimal. Removal of finer slash would have a greater impact because of the larger amounts of nutrients contained; these materials should be left on the site.

INTRODUCED CHEMICALS

Chemical tools used by the forest land manager that may affect residues and residue management decisions include fertilizers, fire retardants, and pesticides. Forest fertilization introduces the largest quantities of chemicals, fire retardant drops result in the highest rates of application, and pesticides probably affect the largest total area. In the following sections, we will examine the distribution and behavior of introduced chemicals and discuss the interactions of these materials with residues and residue treatments.

FERTILIZERS AND FIRE RETARDANTS

Forest fertilization began on a commercial scale in the Pacific Northwest in 1965 and has grown rapidly. In 1971, approximately 100,000 acres (40,470 ha) were fertilized, bringing the total forest land area treated in western Oregon and Washington to over 300,000 acres (121,410 ha). Chemical fertilizers are also the active constituents in fire retardants, and approximately 1.5 to 2 million gallons (5,678 to 7,570 m^3) are applied annually to forest and rangeland fires in the Pacific Northwest. Properties of the chemical formulations vary widely, however, as do the objectives for their use.'

Distribution and Behavior

Initial distribution patterns and behavior of forest fertilizers and fire retardants are affected by method of application. Fertilizers are generally applied by helicopter as a dry, granular formulation; retardants usually are dropped in a liquid formulation directly on or ahead of a fire front from fixed-wing aircraft.

Fertilizers

Commercially important coniferous species in the Pacific Northwest have responded only to additions of nitrogen. Applications have been largely limited to stands of Douglas-fir and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and granular urea (46 percent N) has been the most commonly applied nitrogen carrier (Gessell 1969, Strand and Miller 1969). Application rates vary but are usually 150 or 200 pounds of urea nitrogen per acre (168 or 224 kg/ha).

Urea fertilizer is highly water soluble, and under moist conditions, this form of nitrogen is readily moved into the forest floor and soil. Hydrolysis to the ammonium ion takes place rapidly and is usually complete within 2 weeks. Ammonium nitrogen may be physically adsorbed by various humus complexes, held as an exchangeable cation on organic or mineral cation exchange sites, immobilized by the abundant microbial populations, or utilized by the forest vegetation. Hydrolysis of urea to the ammonium form is accompanied by a marked increase in surface pH.

Applied nitrogen is quickly distributed through the living complex, becomes a part of the nutrient budget, and is cycled within the forest ecosystem (Gessel 1969, Heilman and Gessel 1963). Nitrogen content of the forest floor is increased through direct application and also as the result of increased nitrogen concentration in litter fall. Urea fertilizer also causes other changes in the forest floor by bringing about localized increases in pH. The solubility of organic matter in water is increased; this temporarily increases the rate of decomposition. Downward transport of several cations as well as portions of the original humus nitrogen compounds is increased (Ogner 1972, Overrein and Moe 1967, Crane 1972).

Fire Retardants

Fire retardant chemicals are mixed with water and a'variety of additives, such as thickening agents to regulate viscosity, coloring agents as markers, and corrosion and spoilage inhibitors. Each formulation is designed to meet the needs of specific fire and fuel characteristics and drop conditions. Amounts and kinds of fuel (including residues), the retardant formulation dropped, and existing site conditions, such as previously applied residue treatments, all influence the extent of interaction between residues and introduced chemicals.

Current formulations are composed primarily of diammonium phosphate, ammonium sulfate, monoammonium phosphate, liquid ortho- and poly-phosphates, or urea. All are fertilizer materials and much is known about their behavior in cultivated soils. Extrapolation to forest situations is limited due to greatly different distribution patterns and soil conditions, but many reactions are similar. Thickening agents, such as attapulgite and bentonite clays, are the only additives that may be applied in large enough quantities to have any effect--on heavily treated areas, these materials could increase the cation retention properties of surface layers.

Ground distribution patterns from fire retardant drops vary considerably depending on viscosity of the formulation, drop height, aircraft speed, and wind velocity and direction. In a typical distribution pattern, a total of up to 2 acres (0.81 ha) may receive some retardant, but only 0.25 to 0.50 acre (0.10 to 0.20 ha) receives the minimum effective rate of 2 gallons of retardant per 100 square feet (0.8 liter/m2). Much smaller zones at the center are treated at rates of up to 6 to 8 gallons per 100 square feet (2.4 to 3.3 liters/m^2). Actual application rates of ammonium sulfate can range from 128 lb/acre or 144/kg/ha (0.2 gal/100 ft^2 or 0.08 liter/m^2) near the perimeter to 5,100 lb/acre or 5,716 kg/ha (8 gal/100 ft^2 or 3.26 liters/m^2) at the center of the drop (calculations based on information given by George (1971) for Fire-Trol 100).

In terms of elemental nitrogen, these rates are equivalent to a range of 27 to 1,070 lb N/acre (30 to 1,199 kg/ha). Similar calculations can be made for other retardant materials, and it is readily apparent that very high rates of application of nitrogen and phosphorus occur in the center of the drop zone. However, it is equally apparent that the total area affected by these high rates is relatively small.

Interaction with Residues and Residue Treatments

No data exist on possible interactions between residues or residue treatments and fertilizers or fire retardants. Forest fertilization is still a relatively new practice, and research efforts have been directed toward adequately characterizing nitrogen-responsive sites and developing appropriate application systems. Work with fire retardants has been oriented toward identification of more effective chemicals and formulations as well as development of more efficient fire suppression systems. However, since both groups of chemicals introduce additional plant nutrients, their use could modify nutrient distribution and influence the rate of decomposition of accumulated residues.

Application of presently available firefighting chemicals is equivalent to applying fertilizer nitrogen and phosphorus at rates comparable to those used in forest fertilization (small isolated areas receiving higher rates). Phosphorus usually is not applied at levels in excess of 30 to 50 lb/acre (34 to 56 kg/ha), but acid forest soils characteristically have the capacity to immobilize large quantities of this nutrient, and even the highest rates of application (up to 750 lb P/acre--840 kg/ha) probably will not interact significantly with residues or residue treatments.

Interactions between fertilizer nitrogen and residue treatments will be largely indirect since forest fertilization normally will not coincide with residue treatment. Fertilization will increase the nitrogen content of the forest floor by direct application and by increasing the nitrogen content in litter fall. A single application will have only a short-term effect on nitrogen distribution and probably will not influence residue treatments, but repeated applications at 5- to 10-year intervals will increase the total nitrogen capital and can markedly change the carbon-to-nitrogen ratio of organic residues both on and in the soil. Higher levels of nitrogen in relation to carbon content should result in more rapid recycling of other nutrients as well as nitrogen. The extent of this and the possibility of other effects of repeated applications are not known and should be investigated.

Direct interactions may be brought about by combining nitrogen applications with specific residue treatments. For large accumulations of nitrogen-poor residues, addition of nitrogen could probably be combined with treatments that redistribute chipped or chunked residues. Introduction of new products such as slow release nitrogen fertilizers may alter the kind and extent of interactions with forest residues. These and other possible combinations are discussed in more detail under sections on interactions with soil microbes (Aho 1974, Bollen 1974) and forest disease relationships (Nelson and Harvey 1974).

PESTICIDES

The term pesticide includes chemical insecticides, herbicides, fungicides, and rodenticides.

The four major classes of insecticides are the chlorinated hydrocarbons, organophosphates, carbamates, and pyrethrins. The chlorinated hydrocarbons (DDT, endrin, dieldrin, etc.) are not likely to be used extensively. We limit our discussion to the seed protectant (rodenticide) endrin and DDT.

Malathion (an organophosphate), Zectran and carbaryl (carbamates), and the pyrethrins have largely replaced chlorinated hydrocarbons as insecticides in forestry. The effective persistence of these materials varies from a few minutes for the pyrethrins to a few weeks for the organophosphates and carbamates (Kearney et al. 1969, Warner 1963). They offer practically no opportunity for significant interaction with forest residues.[2/]

Herbicides are the most widel used class of forest chemicals in the Pacific Northwest (Gratkowski 19747. Herbicides most often are applied aerially during regeneration or early stand development or as single stem treatments as the stand matures. Forest residue treatments are most likely to be applied in connection with harvesting or regeneration stages of stand history. Therefore, among pesticides, the herbicides are most likely to interact with forest residues and residue treatments. The orqanic arsenicals (MSMA and cacodylic acid), phenoxy (2,4-D, 2,4,5-T, silvex), picloram, amitrole, and triazines (atrazine) are important herbicides in forestry.

Fungicides are important primarily in nursery practice. Recent restrictions on animal toxins limit the availabil ty of rodenticides. These materia s are not likely to interact with forest res dues under current patterns of use

Pesticide Behavior and the Probability of Pesticide-Forest Residue Interactions

The movement, persistence, and fate of pesticides in the environment is called their behavior. Behavior of a pesticide determines the magnitude and duration of exposure for various organisms and the probability of pesticide-forest residue interactions. Behavior characteristics of pesticides in the forest have been reviewed (Norris and Moore 1971, Norris 1971).

Pesticides applied to single stems are largely confined to treated plants, but aerially applied pesticides are distributed to the air, vegetation, forest floor, and surface waters. Only chemicals in vegetation and forest floor may interact with forest residues.

Significant amounts of most insecticides and herbicides are not likely to persist in vegetation for more than 1 year (Morton et al. 1967, Getzendaner et al. 1969). DDT may persist for 3 or more years (Tarrant et al. 1972). Therefore, unless forest residue treatments are applied within a year of most pesticide applications, no interaction with pesticides in vegetation can occur.

2/ An interaction between a pesticide and a raw or treated forest residue is any alteration of the rate, direction, or nature of pesticide movement, storage, or degradation functions caused by the forest residues or the products of its treatment. We assume pesticide applications will not influence forest residues present when the chemicals are applied.

Forest floor and soil are major receptors of pesticides applied either aerially or to single stems. Pesticides will enter this portion of the forest environment through direct application, in leaf fall, or the washing action of rain on chemicals in air or on leaf surfaces.

Pesticides in the forest floor are subject to storage, movement, and *degradation* functions. These functions are influenced principally by moisture, temperature, soil organic matter, and the level of soil microbial activity, and these factors may in turn be influenced by residue treatments.

Storage *functions*.--Pesticide adsorption on soil constituents is an equilibrium phenomenon particularly important in determining pesticide behavior. Anything which alters the amount or nature of one of the reactants in the equilibrium equation will cause a shift in the amounts of chemical in the adsorbed and free states.

$$\text{CHEMICAL} + \text{ADSORBENT} \underset{k_2}{\overset{k_1}{\rightleftharpoons}} \text{CHEMICAL:ADSORBENT}$$

The nature of the adsorbent material is particularly important in determining the adsorption characteristics of a given soil for a particular pesticide. Most investigators rank adsorbents in decreasing order of affinity for pesticides: Charcoal--organic matter--clay--sand (Richardson and Epstein 1971, Harris 1972, King et al. 1969).

Charcoal produced by burning of forest residues may tightly adsorb subsequently applied pesticides. Organic matter content and cation exchange capacity are both positively and highly correlated with pesticide adsorption (Sheets et al. 1962, Bailey and White 1964). However, amount of organic matter is the best single predictor of pesticide adsorption in soil. The humus and partially decomposed litter are important in pesticide behavior, not the decomposed coarse organic matter such as twigs, chips, etc. Residue treatments which drastically change the nature or quantity of native soil organic matter will influence pesticide behavior to some degree in the forest floor and soil.

Movement *functions*.--Volatilization is an unimportant mechanism of loss for most pesticides from the forest floor. Leaching and surface runoff are competing processes by which chemicals from spray deposits may be moved by water. Rothacher and Lopushinsky (1974) report on the distribution of precipitation between surface flow and infiltration and the impact of forest residues on the infiltration characteristics of the forest floor.

If surface flow of water occurs, the extent of chemical movement with the water will be influenced by (1) distance from site of chemical application, (2) infiltration properties of soil or surface organic matter, (3) rate of surface flow, and (4) adsorptive characteristics of surface materials (Norris and Moore 1971, Trichell et al. 1968).

Leaching or subsurface flow of pesticides is a relatively slow process capable of moving only small amounts of chemical relatively short distances.' The leaching characteristics of a pesticide are inversely related to its adsorption characteristics (Helling 1971). Strongly adsorbed pesticides are not mobile in soil. Therefore, forest residues and residue treatments which influence pesticide adsorption will influence pesticide leaching in a converse manner.

Pesticides move readily in coarse-textured sandy soils, less readily in fine-textured clay or organic soils (Osgerby 1973). Herbicides, in general, are more mobile in soils than are insecticides; however, mobility is relative, and in most cases, even herbicides move only short distances in soil (Harris 1967, 1969).

Degradation functions.--Degradation is the only means by which the total environmental load of a pesticide can be reduced. Pesticide degradation is most often biologically mediated, but chemical degradation is important in the loss of some compounds.

The rate of microbial degradation of pesticides is determined by the susceptibility of the compound to attack and the environmental factors which influence the rates of microbial activities. Environmental factors which favor general microbial activity also favor microbial degradation of pesticides. Bollen (1974) considers the influence of various residue situations and treatments on microbial activities in forest soil,,. Kearney et al. (1969) summarized the persistence in soil of a wide variety of pesticides (fig. 1).

The previous sections provide a conceptual base for understanding pesticide behavior and the factors which influence this behavior in the forest. In the next section, the environmental characteristics of specific vegetation zones are evaluated for their impact on pesticide behavior in general in the "undisturbed" forest. The modifications of pesticide behavior due to production or treatment of forest residues (detailed in a later section) can then be placed in perspective.

Behavior of Pesticides in Vegetation Types

Picea sitchensis Zone

Pesticides, particularly herbicides, are important tools in this zone. The surface soils of this zone are acid and high in organic matter and nitrogen. Temperatures are mild, and moisture is abundant (Franklin and Dyrness 1969). These conditions favor microbial degradation of pesticide residues and minimize movement functions.

Tsuga heterophylla Zone

This wet, mild maritime zone is the most extensive vegetative zone in western Oregon and Washington and the most important for timber production. Soil profiles are moderately deep, and surface horizons are porous, with moderate to high organic matter content (Franklin and Dyrness 1969).

High infiltration capacities limit the probability of overland flow of chemicals, and soil organic matter content is sufficient to limit pesticide leaching. Microbial degradation of pesticides is favored by the abundant organic matter and moisture and reasonably adequate levels of soil nitrogen.

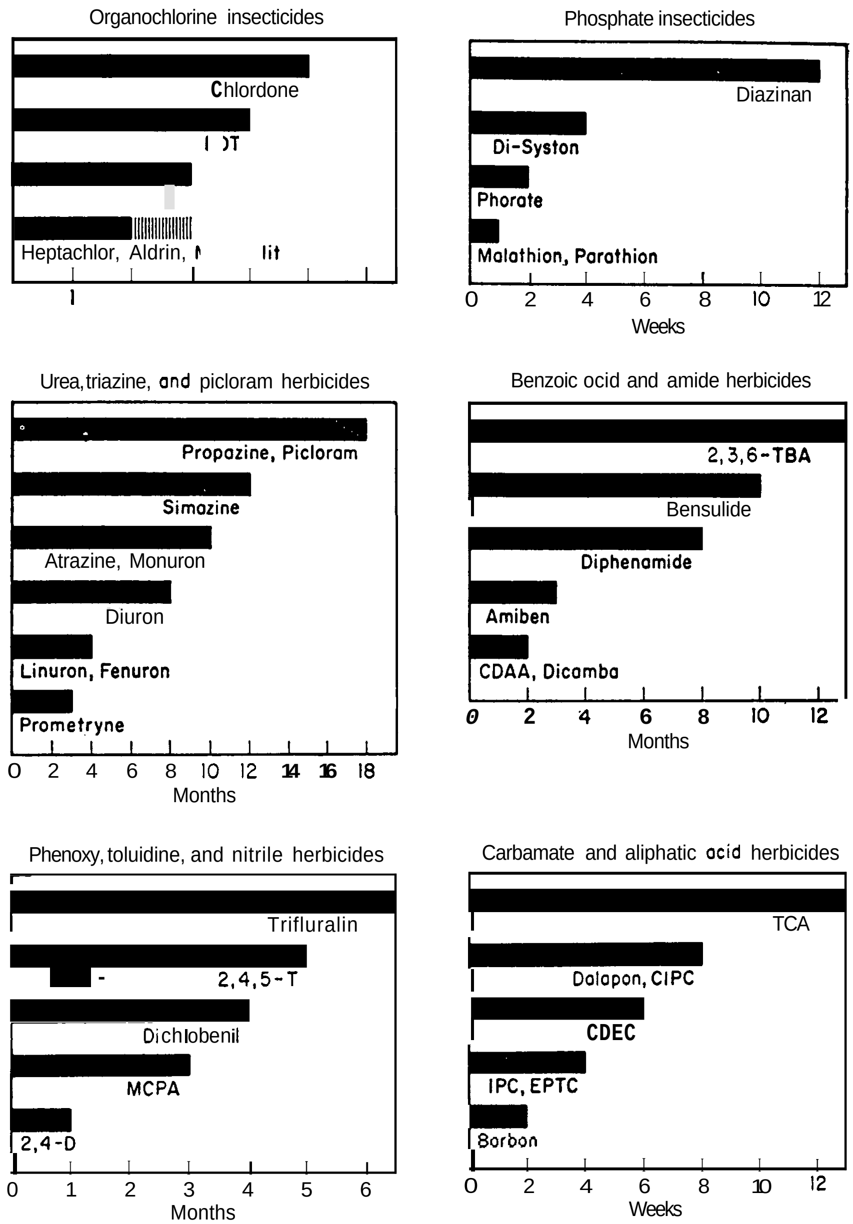

Figure 1.--Pesticide persistence in soil (Kearney et al. 1969, reproduced with permission).

Subalpine Zones

The subalpine zones are generally wetter and cooler than the adjacent *Tsuga heterophylla* Zone, and the soil organic matter content is generally lower. However, abundant adsorption sites may exist in mor humus layers, and extensive pesticide leaching will not occur in this zone. Pesticide persistence will be extended because climatic factors do not favor maximum levels of microbial activity, but pesticides are not used extensively.

Pinus ponderosa Zone

This zone has a short growing season, snow accumulation in winter, and minimal summer precipitation. Coarse-textured soils and moderate to low amounts of soil organic matter suggest the water soluble pesticides may be more mobile in this environment than in other forest zones. However, the low rainfall, characteristic of this zone, reduces the probability of significant pesticide movement. Microbial degradation of pesticides may be retarded by climatic conditions.

Abies grandis Zone

Neither moisture nor temperature conditions are extreme in this zone. Soil profiles are not well developed, but thin mull-type humus layers in some areas and 8- to 9-percent organic matter in A horizons in other areas limit the probability of 'significant pesticide leaching. Moderate environmental conditions favor microbial degradation of pesticides.

Pesticide Behavior in Specific Residue Situations

Most forest pesticides are not persistent chemicals and, unless forest residues are created or treated during the first year after chemical application, there will be no effect on chemical behavior. The probability of a significant alteration of the behavior of a pesticide applied after residue treatment decreases with time as a forest area recovers from residue treatments. The presence or absence of raw undecomposed forest residues probably will not greatly influence pesticide behavior. However, residue treatments which drastically change soil organic matter content, soil infiltration capacity, or the activity of soil microbial populations may exert a significant effect on pesticide behavior.

There are two general pesticide treatment situations which may permit significant interaction of pesticides with forest residues.

1. *The use of herbicides for precommercial thinning or insecticides to protect precommercial stands.* Residue treatment options are limited by the size of the material involved and the difficulty of moving equipment in young stands. If residue treatments are not applied, pesticide behavior will be as outlined for specific vegetation types.

Broadcast burns are probably not feasible in this situation. Various collect-and-burn options may be used, and they significantly reduce pesticide residue levels. Combustion temperature, oxygen availability, and the presence of chemical catalysts may influence the rate and pathway of the thermal alteration of pesticides. The idegtity and behavior of many of the products of pesticide combustion are not known.

Chipping, crushing, or burying operations decrease the probability of pesticide movement to the degree humic matter is added to the forest floor. Such additions of soil organic matter are apt to be slow in terms of the effective life of forest pesticides; therefore, the net effect will be small. Pesticide degradation will vary in proportion to the degree microbial systems are influenced by residue treatment. Bollen (1974) warns that large additions of organic materials, such as processed forest residues, may suppress microbial activities as nitrogen levels are depleted.

2. *The application of insecticides or herbicides to mature stands which will be harvested in a few years; or the application of herbicides for site preparation to aid in regeneration.* The short persistence of the insecticides used in forestry today precludes, in most cases, alteration of their behavior by residue treatments, unless such treatments are applied within a few months of insecticide application. Herbicides are seldom applied before timber is harvested.

Herbicides are used as desiccants in connection with fire to aid in regeneration in some coastal forest sites (Gratkowski 1974). Nearly all the herbicides applied for this purpose will be on the vegetation or the surface of the forest floor when these units are broadcast burned a short time later. Burning is certain to reduce pesticide residue levels, but the possibility that persistent, highly biologically active pesticide combustion byproducts may be produced under these conditions should receive serious attention. Herbicides are not likely to be applied before collect-and-burn types of residue treatments at this stage of stand history.

Insecticides and herbicides may also be applied early in stand history some time after residue treatments are made. If soil organic matter and surface soil structure are altered by broadcast burning treatments, the potential for pesticide movement in overland and subsurface flows will be increased. This may be compensated for to some degree by the production of charcoal. In general, the increase will be small and probably quite restricted. Rapid revegetation of burned areas will ameliorate the effects of burning on pesticide behavior on these sites.

The impact of collect-and-burn treatments will be limited to the areas burned unless serious soil compaction results during residue collection. "Hard burns," likely to result from burning of fuel concentrations, will increase movement and persistence of subsequently applied pesticides', but this effect will be restricted to the hard burned area.

Crushing, burying, and chipping of forest residues which contain pesticide residues may minimize pesticide movement and enhance microbial activities through additions of organic matter to the soil unless soil nitrogen becomes limiting.

A favorable environment for microbial activity exists if nutrient capital is adequate in terms of the amount of organic matter added. Additions of nitrogen, fertilizer may be beneficial in hastening microbial decomposition of both forest and pesticide residues.

The effects of residue treatment on the behavior of subsequently applied pesticide are probably not great. They are not likely to be biologically significant, although there is little doubt that pesticide residue-forest residue interactions do occur.

CONCLUSIONS

Effects of forest residue management on soil processes and introduced chemicals range from limited interaction with pesticides through potential long-term impacts on soil formation to losses of surface organic matter and nitrogen as a result of residue reduction by burning. With the exception of extensive loss of organic matter and damage to soil physical properties caused by wildfires, adverse effects of burning can be avoided or reduced to a minimum by use of available information. From the material reviewed for this paper, we have reached the following specific conclusions.

1. Short-term effects on soil formation are not likely because transformation of parent material into well-developed forest soils is a process that operates on a geological time scale.

2. Residue treatments that increase the frequency of mass soil movements or the amount of surface erosion interrupt the soil development process and reduce site productivity.

3. Intensified forest management, including residue treatment, constitutes a modification in land use that can change the annual rate of addition of organic material to the forest floor. Long-term changes in rate and direction of soil formation are possible. Pleasurement of these changes is difficult, and the effect on productivity is unknown.

4. Nutrient cycling is temporarily interrupted by removal or destruction of vegetation and surface organic layers, but normal cycling is gradually restored by revegetation of the disturbed site.

5. Soil compaction reduces nutrient cycling and the rate of residue decomposition. Soil porosity, aeration, and rate of moisture movement into and through the soil are decreased; thus the level of microbial activity is limited.

6. Severe burning which destroys all the forest floor and all or part of the organic matter in surface layers of the mineral soil breaks a primary link in the nutrient cycle. Soil physical properties also may be seriously damaged and site quality reduced.

7. All types of burning result in some nitrogen loss. Amount of loss depends on the completeness of combustion and the amount and kind of residue burned.

8. Widespread, long-term effects of hard burns are largely limited to wildfires. Although hard burns can occur when piled residues are burned, the affected area is small. Effects of controlled burning are primarily short term.

9. Nutrients other than nitrogen remain in the ash after burning treatments, and their availability is temporarily increased.

10. Nutrient capital contained in organic surface layers and in the organic matter of the surface horizon of mineral soil is extremely important to site productivity even though it may represent only a small percentage of the total nutrient capital on the site. These nutrients are being actively

recycled whereas most of the nutrients contained in the soil are made available only very slowly. Therefore, destruction of surface organic layers will have a significant impact on both nutrient capital and availability.

11. Mechanical treatment of residues to reduce particle size increases the rate of both residue decomposition and nutrient release. Increasing contact with soil will further enhance decomposition.

12. Rapid buildup of microbial populations after addition of large amounts of residue can result in a temporary nitrogen deficiency. Addition of fertilizer nitrogen will enhance decomposition and insure adequate nitrogen for the next crop.

13. Introduced fertilizers and fire retardants add to the nutrient capital, increase the nutrient content of residues, and accelerate decomposition and nutrient cycling.

14. Residue treatment will have only limited effects on pesticide distribution and persistence because residue treatment will seldom coincide with the need for pesticide application.

RESEARCH NEEDED

Little current research is specifically designed to provide guidelines for residue management. Adaptation of existing data and minor modifications of research planned for other purposes will yield valuable information on forest residue relationships.

The influence of natural residues on soil formation and nutrient capital in forest ecosystems is well documented, and current studies under the IBP Coniferous Biome program will provide additional information on the importance of organic residues in nutrient cycling and site productivity.

New research is needed to quantify nutrient levels in manmade forest residues and the effects of residue treatments on nutrient levels, availability, and cycling. Investigations should include effects of residue management in old-growth and second-growth stands, and, if possible, should be designed to provide information on the long-term impacts of intensified forest management on soil formation and nutrient cycling. The effects of various residue management systems on timing of nutrient release and maintaining site productivity are important.

Effects of specific nitrogen fertilizer and fire retardant chemicals on residue decomposition, nitrogen cycling, and the availability of other nutrients need to be investigated. Interactions with different residue situations should be determined and the long-term effects of repeated applications evaluated. Residue situations that require application of fertilizer nitrogen to enhance decomposition or maintain adequate levels of available nitrogen for plant growth during residue decomposition should be identified.

The products of pesticide combustion produced during residue burning have not been adequately studied. Specific research to determine their identity, behavior, and impact in the forest is needed.

EQUIPMENT DEVELOPMENT

Specific guidelines for development of residue reduction equipment should be related to the general need to maintain surface organic layers and minimize nutrient loss and soil disturbance. Equipment that will combine particle size reduction with redistribution over the treated site will conserve nutrient capital and help maintain or improve site productivity. Residue decomposition and nutrient cycling could be further enhanced if equipment design permitted fertilizer application along with spreading of chipped residues when needed. Development of methods and equipment to treat residues on steep slopes should receive high priority.

CURRENT RESEARCH

Several investigations in progress will provide additional information on forest residue relationships and the possible consequences of various residue management practices. Studies under the IBP' Coniferous Biome program are determining the rate of litter production for representative reference stands, the influence of organic composition and nutrient content on rate of decomposition, and the turnover time for litter biomass and nutrients as affected by moisture and temperature. Other studies are examining the mechanisms of nutrient release and transport through the soil system and the extent of nutrient losses due to soil erosion on steep forested slopes. Accumulated data from these and other studies are being integrated into decomposition, nutrient cycling, soil erosion, and hydrological models which will provide the basis for predicting the impact of various stand manipulations including forest residue management. Specific studies that may be of interest are listed below:

Cole, D.W., and S.P. Gessel (University of Washington, Seattle, Washington), Fluxes in soil solution chemistry: A study of the mechanisms and processes involved.

Cole, D.W., and S.P. Gessel (University of Washington, Seattle, Washington), Fluxes in the elemental composition of forest stands.

Fredriksen, R.L., and D.G. Moore (U.S. Forest Service, Forestry Sciences Laboratory, Corvallis, Oregon), Effect of manipulations and vegetation cover conversion on nutrient retention, mobilization, and loss in forest ecosystems.

Kays, M.A., and F.J. Swanson (University of Oregon, Eugene, Oregon), Studies of geology, rock weathering, and sedimentary processes in the H.J. Andrews Experimental Forest.

Strand, M.A. (Oregon State University, Corvallis, Oregon), Prototype modeling of ionic dynamics in the soil solution.

Swanston, D.N. (U.S. Forest Service, Forestry Sciences Laboratory, Corvallis, Oregon), Nutrient losses due to soil erosion on steep forested slopes within the Coniferous Forest Biome.

Ugolini, F.C., and M. Singer (University of Washington, Seattle, Washington), Dynamics of weathering and soil-forming processes.

Ugolini, F.C., and M. Singer (University of Washington, Seattle, Washington), Biogeochemical cycle of the Coniferous Forest Biome.

Additional studies related more specifically to litter decomposition are listed by Dr. Bollen (1974). Other related studies of interest include:

Lavender, D.P. (Oregon State University, Corvallis, Oregon), Nutrient cycle in young Douglas-fir.

Metz, L.J. (U.S. Forest Service, Research Triangle Park, North Carolina), Pioneering research unit in the formation and decomposition of the forest floor.

Stone, E.L. (Cornel1 University, Ithaca, New York), Innovative studies of soil-forest relationships.

Wells, C.G. (U.S. Forest Service, Research Triangle Park, North Carolina), Forest soil productivity in the Southeast.

Youngberg, C.T. (Oregon State University, Corvallis, Oregon), Nature and properties of forest humus.

Zinke, P.J. (University of California, Berkeley, California), Influence of forest vegetation on soil properties.

Current research on introduced chemicals includes continuing studies on the fate and behavior of forest fertilizers and pesticides (Forestry Sciences Laboratory, Corvallis, Oregon). Where possible, these studies will be modified to include interactions with forest residues. One phase of a recently initiated 3-year investigation on the "Entry, fate, and impact of fire retardant materials in forest streams" (Logan A. Norris) will examine the interactions between fire retardants and forest residues.

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SOIL STABILITY AND WATER YIELD AND QUALITY

Jack Rothacher and William Lopushinsky

ABSTRACT

Forest residue activities influence soil and water resources in proportion to the amount they increase soil disturbance. Drastic disturbance of litter and surface soil can' lead to surface erosion and stream sedimentation. Residues and residue treatment would not normally increase mass soil erosion nor ,would water yields change significantly. The quantity of chemicals in streams increases when rate of decomposition of residues exceeds uptake by vegetation. Burning of forest residues increases the quantity of chemicals that may reach streams roughly in proportion to the quantity of fuel burned. Broadcast burning after logging of old-growth Douglas-fir increased loss of nutrient cations 1.6 to 3.0 times that from an unburned area.

Keywords: Soil--erosion, management, stability, compaction; water--quality, yield; watershed management.

INTRODUCTION

Soil and water are basic resources of the forest environment which must be protected if we are to maintain productive soils and clear streams. Litter, dead standing trees, understory vegetation, and natural or man-caused slash constitute residues in the forest environment which can affect soil and water resources through their influence on soil erosion and water yield and quality. In general, residues are beneficial because they protect the soil from erosion resulting from the impact of raindrops, and they prevent movement of dislodged soil into streams. Residues also provide organic matter on and in the soil which is important in maintaining both the texture necessary for adequate infiltration and the fertility of the soil.

Treatments which remove or disturb organic matter protecting the soil surface may increase soil erosion and stream sedimentation. Although protection of the soil surface with a complete cover of organic matter is desirable for good watershed management, it may be in direct conflict with fire protection, silvicultural requirements, and other uses. Perhaps the objective of residue management should be maintenance of an adequate cover of organic matter to protect the soil and water resource and with quantities not so great that they constitute a serious fire hazard or greatly reduce the success of regeneration. The difficulty of reaching this optimum level of residue will, of course, vary with locality and forest type. Slash and understory vegetation occur in smaller amounts in east Cascade forests; but because decomposition is slower under relatively dry conditions, accumulation of residues under natural conditions can be greater than in west Cascade forests (Gessel and Balci 1965). At high elevation where true fir-hemlock forests occur under cool, moist conditions, natural residues may also accumulate because of reduced decomposition (Williams and Dyrness 1967).

In the following sections, we discuss the significant effects of natural and man-caused residues on soil stability and water yields and quality. Soil stability involves two distinct processes, surface erosion and mass soil erosion, although these may occur simultaneously. Since soil erosion is directly related to stream sedimentation, this aspect of water quality is covered in the section on soil stability. The effects of residues on chemical water quality are discussed in a separate section, although Fredriksen (1971) points out that large quantities of chemicals leaving a forested watershed may be found as a component of sediment in streams. The effects of residues on water yield, including seasonal high and low flows, are discussed separately and are largely distinct from erosion and water quality.

Although we have general knowledge of the effects of residues on soil stability and water yields and quality, research relating residues directly to these facets of the forest environment is limited.

SOIL STABILITY

Surface erosion relates to the detachment and transport of individual soil particles (Dyrness 1966). In forested areas, raindrop impact and flowing water are the principal processes involved under moist conditions; and dry ravel, the principal process under dry conditions. Dry ravel is the movement of individual particles downslope by gravity under dry conditions and is common during the summer on steep slopes with little vegetation.

Mass soil erosion, often referred to simply as landslides, relates to detachment and downslope movement of relatively large quantities of soil at one time and occurs primarily during wet soil conditions with gravity as the moving force.

SURFACE EROSION

In virtually all forests in the Pacific Northwest, surface erosion is minimal under undisturbed conditions (Rice et al. 1972). Any activity that removes the protective organic material making up the forest floor may increase surface erosion and subsequently stream sedimentation.

Natural Residues

Under natural conditions, the forest floor is composed of fresh litter on the surface over layers of partially to completely decomposed organic material which grades into a mixture' with the mineral soil. The distribution of organic matter in a young Douglas-fir (*Pseudotsuga rnenziesii)* forest is shown in table 1.

Table I.--Distribution of N, P, K, Ca, and organic matter (kg/ha) in a secondgrowth Douglas-fir ecosystem[1/]

Component		N	P	K	Ca	Organic matter
TREE						
Foliage	current	24	5	16	7	1,990
	Older	78	24	46	66	7,107
Branches	current	4	1	3	2	513
	older	40	9	32	65	13,373
	dead	17	2	3	39	8,145
Wood	current	10	2	10	4	7,485
	older	67	7	42	43	114,202
Bark		48	10	44	70	18,728
Roots		32	6	24	37	32,986
Total tree		320	66	220	333	204,529
SUBORDINATE VEGETATION		6	1	7	9	1,010
FOREST FLOOR						
Branches		5	1	4	8	1,423
Needles		35	4	5	27	3,005
Wood		14	2	8	17	6,345
Humus		121	19	15	85	11,999
Total forest floor		175	26	32	137	22,772
SOILS						
0-15 cm		809	1,167	79	313	38,372
15-30 cm		868	1,195	66	196	36,935
30-45 cm		761	980	52	152	28,290
45-60 cm		371	536	37	80	7,955
Total soil		2,809	3,878	234	741	111,552
TOTAL ECOSYSTEM		3,310	3,971	493	1,220	339,863

[1/] From Cole *et* al. 1967 (used with permission).

Organic compounds in the surface soil often aggregate fine soil particles and improve infiltration properties of the forest soils, thereby minimizing surface erosion. The coarser organic particles of the forest floor intercept raindrops and protect soil particles from detachment and puddling. Because of high infiltration rates in surface soils under the forest floor, surface runoff is rare under undisturbed forests. High infiltration rates are, in-part, the result of macropores in the soil from animal activity and root decay channels. Overland flow during the snowmelt season has been observed on both disturbed and undisturbed forest floors where the terrain is glaciated and the water table is high (Burroughs et al. 1972).

Catastrophic events such as windthrow, snowbreakage, and death of forest trees by insect or disease have little effect on surface soil erosion. With the exception of root holes where windthrown trees stood, these events result in a temporary increase in the litter layers of the forest floor. Root holes are depressions and are sufficiently discontinuous that any movement of soil particles is local, and stream sedimentation is minor. An exception might be streambank trees that are windthrown, opening bare soil to erosion directly into the stream, or that obstruct normal flow of the stream and cause channel changes and bank cutting.

Wildfire, by removing the litter layer, may have an appreciable influence on surface soil erosion. Dyrness (1966) concluded that severe burns result in serious soil erosion; light burns have negligible effects. He cited several studies in chaparral in which increased infiltration followed light burning (Burgy and Scott 1952, Scott 1956, Scott and Burgy 1956) and in which surface erosion might actually have been reduced. Serious uncontrolled fires usually burn under dry conditions in which overstory trees are killed and almost all the forest floor is consumed, leaving bare mineral soil exposed. These are optimum conditions for increased soil erosion which can be dry ravel on steep slopes or sheet erosion and rilling.

Surface erosion on severely burned slopes is most serious where soils are inherently highly erodible (granodiorite, pumice, and other single grain soils) and where high intensity precipitation occurs as it occasionally does in eastern Oregon and Washington. Perhaps the best evidence of the effect of wildfire on surface erosion is that from the Entiat Experimental watersheds in the Wenatchee National Forest of eastern Washington which were burned over by a severe forest fire in 1970. Before the fire, two of the three watersheds, which range from 1,200 to 1,400 acres (486 to 567 ha) in size, produced practically no sediment, and the third produced approximately 20 yd^3 (15 m^3) annually. In 1971, 1 year after the fire, sedimentation from each of the three watersheds ranged from 53 to 166 yd^3 (41 to 127 m^3). This increased sedimentation largely resulted from accelerated channel cutting caused by increased streamflow rather than increased surface erosion. In 1972, after a high intensity rainstorm, surface erosion occurred mainly in areas where the soil surface had been disturbed and compacted, reducing infiltration. For example in salvage logging areas, skid trails and roads concentrated overland flow into nonnatural channels in which gully erosion developed. On undisturbed areas without vegetation cover, some surface erosion was observed; but where vegetation had become established, surface erosion was minimal in spite of considerable overland flow.

Few other studies of postwildfire erosion have been made in the Northwest, probably because accurate estimates of changes in soil loss are difficult when background data are not available or because the damage is so obvious. In 1953, Sartz studied the 1951 West Hills fire near Portland. After a severe fire on steep slopes, he estimated erosion from 32 inches (81.3 cm) of rain between October 17 and May 2 removed an average of 0.12 inch (0.3 cm) of soil. By May 2, a cover of vegetation had been reestablished which provided effective control against further sheet erosion on most of the area.

Surface erosion on severely burned areas also occurs as dry ravel from steep slopes during summer months. Mersereau and Dyrness (1972) estimated over 12,000 ft3 (340 m^3) of soil moved by dry ravel during parts of two summer seasons from the over 60-percent slopes of a 237-acre (96-ha) slash-burned watershed (55-percent bare soil after burning). Presumably, conditions would be similar in a wildfire area. As in Sartz's (1953) study, measurement of dry ravel was stopped the second year because revegetation had virtually stopped accelerated soil loss.

Research has shown that hot fires often leave a nonwettable soil (DeBano and Krammes 1966, DeBano 1969, DeBano et al. 1970). The greater the intensity of the fire, the greater the nonwettability. This condition results in decreased infiltration and increased surface runoff and erosion. Unpublished studies on pumice-derived coarse textured soils in the "Airstrip Burn" of 1967 in the Oregon High Cascades show that nonwettability continues for several years. Nonwettable soils may reduce the rate of revegetation of the area. Osborn et al. (1964) treated a nonwettable soil with a wetting agent and found a fourfold increase in vegetation.

Manmade Residues

Manmade residues provide protection to the soil surface similar to natural residues. Large quantities of fresh material are added during logging although quantity and distribution vary with silvicultural system and yarding method. Dell and Ward (1971) measured fuel weights of 32 to 227 short tons/acre (72 to 509 metric tons/ha) and volumes of residues averaging 7,430 ft^3/acre (519 m^3/ha) in Douglas-fir forests in western Oregon and Washington. Table 2 shows Dyrness' (1965, 1967, 1972) findings on slash density for several yarding systems. These results indicate that about three-fourths of a clearcut area had some slash providing a degree of protection from surface erosion.

Other silvicultural systems, which would remove a smaller portion of the forest stand, would presumably add less manmade residue but might leave more of the natural residues undisturbed.

Similarly, cultural practices such as thinning, pruning, and herbicide or silvicide treatments would add increased fresh residues to the forest floor but would cause relatively minor changes in natural forest residues and little change in surface erosion.

Heavy accumulations of residues from initial stages of mill processing such as bark slabs and sawdust piles also protect the soil surface from erosion. This surplus would be reduced by residue treatments.

We should recognize that manmade slash, especially cull logs left crossways on steep slopes, may be beneficial by catching and holding eroded material on the site and out of stream channels.

Table 2.--Slash density as percent[1] of total clearcut area by four yarding systems

Slash density	Tractor	High-lead	Skyline	Balloon
Heavy	25.4	26.9	10.8	20.2
Light	42.6	37.7	53.8	52.6
Absent	26.4	25.9	32.2	21.3
Cull log	6.3	9.9	6.4	5.9
Percent bare soil	([2])	14.8	12.1	6.0

[1] Percentages by density do not add to 100 because cull logs and both light and heavy slash can be recorded on one plot. Also, absence of slash and bare soil can be recorded on the same plot.

[2] Not recorded.

Several user guides (Kidd 1963, Haupt 1959, Packer and Christensen 1964) have been developed for the drier pine sites of the interior West which recommend systematic approaches for using residues in erosion control. Perhaps because quantities of natural and manmade residues are so large and revegetation so rapid in most areas west of the Cascade Range, residues are seldom deliberately placed to control erosion. Undoubtedly situations occur in west coast forests where logging slash and other debris could be used to control erosion from disturbed sites.

Residue Treatments

In surface soil erosion, residue treatments are important in relation to the amount of soil disturbance they cause or prevent.

No Treatment

Unless the benefits of soil protection are exceeded by esthetic, fire hazard, or silvicultural considerations, it is best to leave slash without further disturbing the site. Redistribution of forest residues may be beneficial in some cases, if this can be done without further soil disturbance or exposure.

Rearrange and Leave

Treatment by hand, such as lopping and scattering or piling, can be accomplished with minimum soil disturbance. On excessively erosive sites such as the granodiorite soils of the Tiller District in the Umpqua National Forest of southwestern Oregon, slash has been effectively distributed over road fill slopes either by hand or by machine to provide some additional protection from surface erosion of newly placed soil.

In areas of similar highly erosive soils in the Boise basin of Idaho, Haupt and Kidd (1965) used slash for skid trail barriers to retard soil movement. In this low rainfall area, similar to eastern Oregon and Washington pine forests, slash placed in dry draw bottoms can act as sediment filters or traps, although there is risk of movement during high intensity storms. In the much higher precipitation zones west of the Cascade Range, Rothacher (1959) warns that slash left in channels draining 40 acres (16 ha) or more may be moved by large storms to form small debris dams and cause increased erosion downstream.

In general, machine piling, windrowing, yarding unutilized material (YUM), dragging, or moving slash to a hole or other disposal site involve varying degrees of disturbance and exposure of the soil. However, cut logs placed across the slope can be beneficial; they trap material moved by surface erosion. Tractor piling and windrowing slash on gentle slopes and heavy soils at the Umpqua Experimental Forest were observed to greatly increase surface erosion due to compaction, reduced infiltration, and exposure of the mineral soil.1/ YUM yarding in the same area left the forest floor disturbed but the soil surface relatively well protected by organic matter mixed with surface soils.

Treat Mechanically and Leave

Chipping of forest residues with redistribution of chipped material over the soil surface may be a desirable practice, especially along road rights-of-way where chips could be used to protect cut and fill slopes. In central Idaho, a 1-inch-thick (2.54-cm) layer of wood chips spread over the tread of logging roadbeds had a slight adverse effect on the rate of establishment of reseeded grasses (Kidd and Haupt 1968). An adequate supply of fertilizer could be used to counteract this effect. In large scale disposal of forest residues on steep ground, yarding logs to the chipper or moving the machinery might create more disturbance. Tractor operations on Forest Service lands are generally restricted to slopes under 30 percent. Above this, slopes are thought to be too steep for safety and machine stability unless tractor roads are cut into the slope, which would further disturb the site. On gentle topography, chipping and spreading of chips could control surface erosion even on a severely disturbed area.

Crushing with heavy equipment, such as the Tomahawk cutter-crusher, should be restricted to more gentle topography (under 20 percent) and operated across the slopes.

Burying of forest residues would cause excessive disturbance locally and could further disturb areas from which debris is moved.

Any operation using heavy machinery should be restricted to avoid areas or times when compaction of soil would be expected. Surface runoff and erosion may be greatly accelerated if infiltration is reduced through compaction of the

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1/ Unpublished information on file at Forestry Sciences Laboratory, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon.

surface soil. In 1959, Lull prepared an excellent summary of soil compaction of forest and range lands, which should be consulted before use of heavy machinery to treat forest residues is considered. He points out that some compaction can be expected with any use of the forest. Compaction increases bulk density--reduces total pore space by the same proportion, reduces noncapillary pore space a greater amount--and has its greatest effect on infiltration and percolation of water.

The resistance that the soil offers to compaction depends on the moisture content, texture, structure, density, organic content, and, of course, the forces applied. As soil moisture content increases, compaction may result even though loads are reduced; or restated from the viewpoint of this report, the same amount of damage can be inflicted on wet soil with light equipment as on much drier soils with heavier equipment. Maximum compaction results at a moisture content midway between field capacity and wilting point--approximately the moisture content at which soil can be rolled in the hand into 1/8-inch-diameter (0.32-cm) threads. In general, soils with the greatest range of particle sizes compact to the greatest densities. Hardpans produced by compaction from vehicles are most commonly found in medium textured loam soils--sandy loam and silt loams.

Figure 1 (Lull 1959) illustrates the relationships between soil moisture and bulk density as influenced by variations in load and soil texture. Engineers use this type of curve to determine the moisture content needed for maximum compaction for a given soil. The same curves could be developed to determine moisture content at which compaction could be minimized. Unfortunately, especially west of the Cascade Range, forest soil remains at a moisture content conducive to compaction most of the year. Well-aggregated soils, such as are found in many forest areas, have lower bulk densities than those in figure 1 and are highly permeable. Under compaction forces, the aggregates are crushed, particles fill the interaggregate spaces, and permeability is reduced. The greater the organic matter content of the soil the less the susceptibility to compaction.

The degree of compaction varies with the kind of residue treating equipment. Crawler tractors compact the soil less than wheel vehicles do. Compared with an assumed average ground pressure of 7 lb/in^2 (0.5 kg/cm^2) for crawler tractors, pressures of agricultural tractors average about 20 lb (1.4 kg), passenger cars 30 lb (2.1 kg), and trucks 50 to 100 lb/in^2 (3.5 to 7.0 kg/cm^2). The weight of equipment used may not be important considering the pronounced compaction influence of relatively small ground pressures. Crawler tractors, with smallest ground pressures, can have a major effect on the soil. Under wet conditions, for example, one pass of a tractor has been known to reduce macroscopic pore space by half and infiltration rates by 80 percent. The factor influencing compaction that is most susceptible to management is the area of disturbance. The simplest way to control compaction, like erosion, is to prevent it. This could be most easily accomplished by restricting use of heavy equipment for residue treatment to existing road systems.

Burn

Periodic prescribed burning has seldom been practiced in the coastal areas of the West but has been used in east Cascade ponderosa pine *(Pinus ponderosa)* forests. As with light wildfires, light burning apparently does not decrease infiltration. Intense precipitation would be expected to result in increased erosion of bare soil.

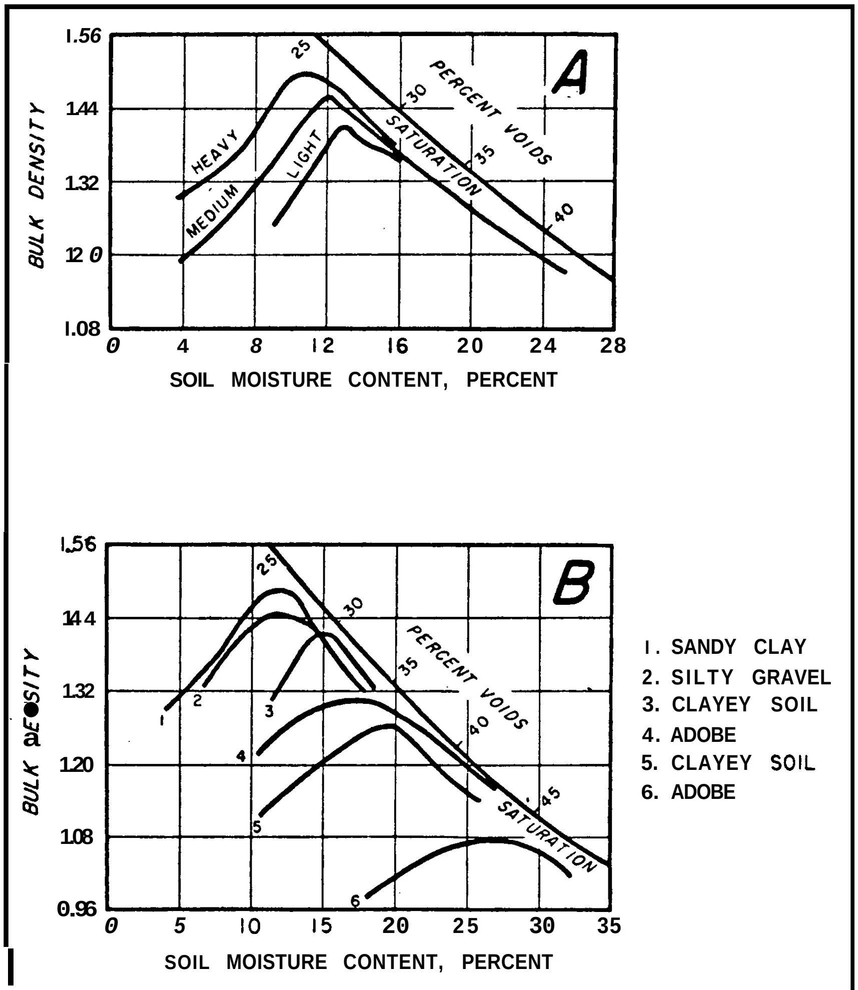

Figure 1.--Basic relationships between compaction and soil moisture content as affected by A, light, medium, and heavy loads; and B, soil texture. Bulk density is defined as mass per unit volume. (From Lull 1959.)

Broadcast burning in heavy slash is done when soils are moist but slash is sufficiently dry to spread fire. Under these conditions, Tarrant (1956) and Dyrness and Youngberg (1957) found extensive unburned and lightly burned areas, with maximums of only 5 to 8 percent severely burned. In severely burned areas, infiltration rates may decrease, but rates change little in lightly burned areas.

Mersereau and Dyrness (1972) reported bare soil on the steep slopes of an experimental watershed increased from 12 percent after logging to over 55 percent after broadcast slash burning. They found that slope steepness, aspect, and vegetative cover have a strong influence on accelerated surface erosion. After broadcast burning, soil movement was 4-1/2 times greater on 80-percent than on 60-percent slopes; almost 3-1/2 times greater on south slopes than on north slopes; 46 times greater on bare 80-percent slopes than on vegetated 60-percent slopes. For the entire 240-acre (97-ha) watershed, an estimated 458 yd^3 (350 m^3) of soil moved downslope during a 16-month period. On the same watershed, Fredriksen (1970) measured suspended sediment concentrations 67 and 28 times that from the undisturbed watershed during the first and second years after slash burning. Coarse sediments increased to over 30 ft^3/acre (2.1 m^3/ha) compared with 0.1 ft^3 (0.007 m^3) in the undisturbed watershed. Probably a major portion of the sediment came from channel cutting in material previously deposited in the streambed with an unknown quantity from the steep side slopes.

Burning damage to the soil from piling and burning residues would be limited to those areas beneath the piles. These would be similar to severely burned sites where Tarrant (1956) found decreased infiltration and reduced rates of revegetation. Since piles would represent a small portion of the total area, soil erosion leading to stream sedimentation would probably be minor. If piles were constructed with machinery that severely disturbed the surface soil, considerable surface erosion would be expected. Pit burning would limit soil damage from fire to one site; but surface erosion would depend on the degree of excavation surrounding the pit and disturbance resulting from moving residues to the pit. Burning residue in portable bins would cause no fire damage to the soil surface. The effect of this system on soil erosion would depend on damage to the soil by bin feeding or transporting equipment, which could be considerable.

Wildfire in manmade residues generally occurs when soil and fuels are driest and would be expected to cause the most severe burn. Severe fires in the Pacific Northwest have been reported to reduce organic matter content in the surface 2 inches (5 cm) of the mineral soil by 61 to 75 percent (Austin and Baisinger 1955, Youngberg 1953, Dyrness and Youngberg 1957). Organic matter is an important cementing agent in soil aggregate formation and indirectly influences infiltration.rates. Dyrness and Youngberg (1957) found an 18-percent decrease in amount of soil aggregates in severely burned areas.

Lower infiltration and increased soil nonwettability of coarse, sandy-textured soils following severe wildfires would increase surface runoff and erosion more on areas disturbed by logging than on natural areas or on prescribed burns of either natural or manmade residues.

Removal of Residues

No known studies have reported on soil erosion after removal of salvage logs or whole trees. The effect on surface erosion and stream sedimentation would be related to soil disturbance (Megahan and Kidd 1972). Whole tree logging would involve fewer trips and possibly less disturbance for the entire process of yarding and slash disposal. There would be little residue added to natural residues other than branches and tops which vary with stand defect and breakage in logging.

Removal of all large material as in YUM yarding may disturb much of the soil, but this does not necessarily result in conditions conducive to increased surface erosion. However, on excessively steep slopes (over 60-80 percent for most soils), soil is approximately at the angle of repose. Removal of debris that bares the soil will inevitably result in downslope movement of soil particles. Such areas should be left unlogged or every effort made to retain a well-distributed cover of debris over the entire area. If left, cull logs would be most beneficial across the slope.

MASS EROSION

Residues and residue treatment probably have little direct effect on mass soil erosion unless slope stability is severely altered as might occur if additional roads were required across steep slopes to remove or rearrange residues. Swanston[2] suggests that shallow noncohesive soils on slopes greater than 37° are basically unstable. Slopes from 28° to 37" approach the critical angle and might fail if disturbed. Cohesive soils (high in clays) may be stable at vertical angles when dry but have virtually no internal strength when saturated.

Residues may indirectly contribute to mass erosion. For example, in steep terrain, logging slash may be moved downslope by small slides of saturated soil to block stream channels. This, in turn, can result in large debris-mud torrents causing severe mass erosion. Any logging debris left in stream channels will increase the chance of channel blockage.

In southern California, fire has been thought to have some influence on landslides through its effect on infiltration. Reduced infiltration which prevents high levels of soil water makes slopes less suceptible to mass movement, at least temporarily, Foggin[3] estimated landslide erosion in an unburned drainage was 1,800 metric tons/km^2 (5,139 short tons/mi^2); in a recently burned drainage, 1,100 tons (3,140 short tons). However, this may be short lived. Rice and Foggin (1971) suggest that, when the roots of fire-killed vegetation on a 9-year-old burn began to rot, there was a period when susceptibility to landslides was worse than immediately after fire or with full vegetative cover. Usually, because of destruction of water-using vegetation, fire can be expected to increase soil water content, resulting in more rapid saturation during the recharge period. Studies on the burned Entiat watersheds (Klock 1972) showed that in the fall, 1 year after the fire, the upper 4 feet (1.2 m) of soil profile contained 5 inches (12.7 cm) more water than was contained in the soil during the same period before the fire.

2/ D.N. Swanston. Unpublished information on file at Forestry Sciences Laboratory, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon.

3/ G.T. Foggin. Unpublished data on file at Pacific Southwest Forest and Range Experiment Station, Glendora, California.

WATER YIELD

Almost no research deals specifically with the effect of residue or residue treatment on water yield. But from associated studies, we know that water yield is greatest from areas with minimum vegetation combined with dead shade which reduced evaporation.

Natural Residues

Litter and standing dead vegetation provide shade and insulation to the soil surface, reducing evaporation of water. Reduced evaporation theoretically would make more water available for streamflow, although whether this would be a measurable quantity is questionable. As discussed under surface erosion, litter and natural residues protect the soil surface and maintain a high infiltration rate. Where high intensity precipitation occurs, high infiltration rates reduce surface runoff preventing excessive peak flows. On the other hand, peak flows may be increased when infiltration is reduced after a wildfire which burns the soil surface clean and produces a hydrophobic soil condition. Studies in the Entiat watersheds show earlier and higher peak snowmelt runoff after the fire of 1970 (Helvey 1972).

Manmade Residues

Residues from timber harvest, cultural practices, or processing provide added shade and insulation to the soil surface, although the operation may leave an uneven distribution that is less effective than smaller quantities of more evenly distributed natural residues. At high elevations where snow is a major source of water for streamflow, Anderson (1963) found that snow melted faster on heavy slash areas than where it was in contact with the ground surface. He suggests that slash should be removed from areas cut with the intent to accumulate and delay snowmelt runoff. Under some conditions, slash windrowed at the lower edge of strip cuttings trapped cold air and prevented snowmelt in winter. Strategically located windrows of slash could act as snow fences to trap more snow in exposed places, although research along this line has been limited to cutting patterns and the use of slatted snow fences.

Residue Treatments

The effects on total water yield of various methods of treating residues probably are minimal compared with reduction of transpiration through removal of vegetation. There is some evidence that soil conditions after residue treatment can influence peak flows.

No Treatment

The influence of leaving postlogging residues as they lie depends on their distribution over the area. Evenly distributed slash provides the greatest soil protection from evaporation but may increase interception of rain and snow. As mentioned above, we have evidence that snow intercepted by slash melts faster than that on the ground.

If slash is unevenly distributed, as when separated by skidroads uphill and downhill, more rapid surface runoff in skidroads may result in increased peak flows.

Rearrange and Leave

Hand piling, cat piling, windrowing, or other rearrangement of slash probably would have little effect on water yields or timing of streamflow unless machine-caused disturbance is sufficient to cause increased surface runoff. Increased evaporation resulting from greater exposure of soil surface is unlikely to measurably affect water yields, although information concerning this effect is lacking.

Treat Mechanically and Leave

Chipping or other operations that would reduce the size of residues and redistribute them uniformly over the soil surface could conceivably decrease evaporation from the soil, reduce surface runoff, and delay snowmelt. Theoretically, water yields would increase, and peak flows could decrease, but whether the quantitites would be significant is not known.

Burn

Prescribed light burns and burning in portable bins would remove larger slash accumulations but leave some organic matter at and incorporated into the soil surface, with probably only minimal influence on water yields or timing.

Piling and burning, pit burning, and similar treatment of residues would increase the area of soil left without organic protection, leading to higher evaporation and greater surface runoff.

Broadcast burning would again expose more soil, leading to greater evaporation. Hot fires on some sites result in a hydrophobic condition that increases the opportunity for surface runoff and higher peaks. However, on a watershed at the H.J. Andrews Experimental Forest, we were unable to detect any effect on water yields or on peak flows from slash burning in addition to those increases resulting from clearcut logging alone. This would indicate that transpiration from postlogging vegetation destroyed by the fire plus evaporation from exposed soil is small compared with transpiration of the heavy timber stand removed by logging.

Wildfires are similar to broadcast burns but generally are hotter with increased effects. We have no research evidence, but it seems unlikely that the increased effect would be sufficient to cause changes appreciably greater than those resulting from the logging operation.

Snowmelt on areas burned by wildfire may be accelerated by the presence of standing blackened trees. Also, disturbance from salvage logging of fire-killed timber during winter months probably alters the surface albedo and may hasten snowmelt to an unknown extent. Almost all snow studies in the deep-snow areas of the Cascade Range show that snow remains later in the year under a stand of trees compared with large openings. However, there are some indications that snow may actually disappear a few days earlier under a stand of mature trees than in small openings of various sizes on leeward, north slopes below 5,000 feet (1,524 m) in the intermountain region.

Physical removal of residues in the above cases would not be expected to - have an appreciable effect on water yields.

WATER QUALITY

Forest residues represent a portion of the cycle of nutrients in the forest and in the aquatic ecosystem. The nutrient cycle is discussed in more detail by Moore and Norris (1974) in their chapter on soil processes; only that portion directly related to chemical water quality will be discussed here. Although vegetation influences water quality in several ways, climate and especially the geology of the area may be even more important. Fredriksen (1971) has demonstrated that considerable portions of the nutrients carried from the land to water are attached to eroded soil particles. Other aspects of water quality influenced by forest residues such as water temperature, debris dams, and oxygen content are covered by Brown (1974) in his chapter on stream conditions and fish habitat.

In one sense, chemicals in stream water, whether dissolved or attached to sediment, represent a loss to the nutrient cycle within the forest. Considerable effort is being made (Fredriksen 1972, U.S. International Biological Program, Analysis of Ecosystems 1971) to better understand the nutrient cycle and whether chemicals carried by a stream are in excess of needs of the forest environment or whether they indicate significant loss of nutrient capital, which in turn represents deterioration of the site. Our discussion does not deal with this question but does provide information on the influence of residues and residue treatment on levels of chemicals in stream water. When appropriate, these levels will be related to water quality standards.

Natural Residues

Natural residues are part of the vegetative cycle. The chemicals they contain will largely be recycled within the forest ecosystem with only slight losses under natural vegetative conditions (Fredriksen 1972, Gessel and Cole 1965, Cole et al. 1967). Since release of chemicals is closely related to rates of decomposition (Mitchell and Sartwell 1974, Aho 1974, Bollen 1974), normal accumulation of residues and accelerated accumulation, as from windthrow and breakage, would have little influence on water quality unless other factors increase decomposition rates.

The living and dead organic materials that comprise the forest are rapidly oxidized by fire leaving small amounts of ash. With subsequent precipitation, a portion of the chemicals dissolved from the ash reaches streams (Fredriksen 1971). Grier and Cole (1971) simulated broadcast slash burning on plots covered with needles, branches, and tops of trees at the rate of 13.8 lb/yd^2 (7.5 kg/m^2) and 59 lb/yd^2 (32 kg/m^2). They found that slash burning caused substantial increase in the concentrations of ions entering the soil and an increase in ion loss from the rooting zone. The increases in leached ions were related to the weight of fuel on the surface. Probably the most current information on the release of chemicals after wildfire comes from the Entiat watersheds where the chemical quality of stream water before and after fire has been studied.

In a study near the Entiat Watersheds, Grier (1972) showed that the ash layer after fire included 193.6 lb (217 kg/ha) Ca, 52.6 lb (59 kg/ha) Mg, 34.8 lb (39 kg/ha) K, 6.2 lb (6.9 kg/ha) Na, and 18.7 lb (21 kg/ha) organic N per acre. Of these amounts, 31 percent of the Ca, 80 percent of the Mg, 85 percent of the K, and 90 percent of the Na moved from the ash into the soil with the first snowmelt after the fire. Eighty to 90 percent of the Ca, Mg, and K were retained in the upper 14 inches (35.6 cm) of soil; but only 20 percent of the Na was retained.

Water chemistry studies conducted by Tiedemann (1973) on the experimental watersheds showed that before the fire, nitrate-N concentration ranged from less than 0.005 p/m during periods of relatively low flow to 0.016 p/m during spring runoff. During the first spring runoff period after the fire, nitrate-N concentration increased to a peak of 0.095 p/m and, during the following summer and fall, declined to prefire background levels. During the winter, nitrate levels then began to increase, and during the second spring runoff after the fire, nitrate-N concentration peaked at 0.560 p/m. Although this concentration is considerably above prefire background levels, it is substantially below Federal water quality standards. Total annual nitrate-N loss the first year after the fire was 0.07 lb/acre (0.08 kg/ha) and the second year 1.92 lb/acre (2.2 kg/ha), compared with 0.008 lb/acre (0.009 kg/ha) before the fire. After the fire, measurements made on a nearby unburned watershed showed that, before spring runoff, the concentration of nitrate-N increased to 0.067 p/m; but by the time of peak spring runoff, the concentration had declined to background level.

Average Ca concentrations of stream water for three watersheds in the same area declined from 8.8 p/m before the fire to 7.3 p/m 1 year after the fire, and to 5.0 p/m 2 years after the fire. Average Mg concentrations for the same periods were 1.5 p/m before the fire, 1.3 and 0.9 p/m after the fire. Na concentration declined from 2.9 p/m before the fire to 2.3 p/m 2 years after the fire. These declines in concentration apparently resulted from dilution caused by increased runoff. Loss of total cations (Ca, Mg, K, Na) increased from 19.3 kg/ha/yr (17.2 lb/acre/yr) before the fire to 31.7 kg/ha/yr (28.3 lb/acre/yr) 1 year after the fire, and 60.6 kg/ha/yr (54.1 lb/acre/yr) 2 years after the fire.

Johnson and Needham (1966) found no specific effect of fire on the ionic composition of stream water following a forest fire in California. They postulated that, because of the acidic nature of the soil, the cations leached into the soil were adsorbed on the exchange complex rather than washed directly into the stream.

Manmade Residues

The main difference between natural and manmade residue is the large, concentrated volume after timber harvesting and, to less degree, from cultural practices. Bark, slab, and sawdust piles left by portable processing equipment are extreme examples of concentrations of organic matter. We know of no studies that relate these concentrations to water quality provided the concentrations are not deposited in the water itself. The chapter on fish habitat by Brown (1974) discusses the importance of residues in streams. Fredriksen's 1971 study of chemical quality of water during logging, when the stream from a 240-acre (97-ha) watershed was largely buried in logging debris, shows a gradual rise in disssolved chemicals during the 4 years required to complete logging. Analysis of individual chemicals showed the largest increase during the warm season of the year. Release of these chemicals may be due, in part, to accelerated decomposition of logging residues.

Increased .cation loss may be related to increased bicarbonate ion levels resulting from microbial activity. Studies by McColl and Cole (1968) on cation transport in forest soils indicate that bicarbonate ions resulting from root respiration, microbial activity, and the atmosphere are the principal source of anions to the soil system, and that activity of cations in the soil solution is directly related to bicarbonate activity. Release of chemicals may also be due in large part to the drastic reduction in vegetation available to use the chemicals after logging. In Fredriksen's study, levels of chemicals measured did not exceed water quality standards during the logging operation but did for a brief period after burning. Cultural treatments of forest vegetation with pesticides, fertilizers, and other introduced chemicals are discussed in the chapter by Moore and Norris (1974).

Timber harvesting practices that disturb natural residues and unevenly distribute logging residues not only increase surface erosion but also increase the chemical load in streams. Fredriksen (1970) estimated that slightly over 50 percent of the nitrogen loss after burning was associated with sediment.

Residue Treatments

Except for studies of burning, we have almost no evidence of the effect of various treatments of forest residues on water quality.

Treatment that would rearrange or change the size and form of forest residues or influence the moisture and temperature relations could have a minor effect on.water quality by changing the rate of release of chemicals during decay. Factors affecting decay rate of residues are covered in the chapter by Aho (1974). Once the chemicals are released, their movement is influenced by the vegetational uptake, capacity of the soil to absorb them, ion transport mechanisms within the soil, and the availability of water to transport them to streams and lakes.

In warm, moist areas, rates of decay would be relatively rapid, but uptake of nutrients by rapidly developing vegetation would also be increased. Marks and Bormann (1972) have shown the rapid increase of nutrients in vegetation during early stages of succession after timber cutting. The opposite condition exists in dry country where decay is relatively slow and vegetation development is retarded. So, even treatments such as chipping, which should speed decay, would be unlikely to appreciably affect water quality as long as residues are not in direct contact with water.

Burning, as discussed under natural residues, greatly accelerates release of chemicals, some of which reach streams and influence water quality. In the streams draining a steep 240-acre (97-ha) experimental watershed, Fredriksen (1971) measured sudden large increases in most chemicals immediately following broadcast slash burning of the entire drainage. In his study in a Douglas-fir forest (*Tsuga heterophylla* zone), loss of nutrient cations after logging and burning increased 1.6 and 3.0 times loss from an undisturbed watershed. A surge of nutrients contained concentrations of ammonia and manganese that exceeded Federal water quality standards for about 12 days. For 2 years after burning, annual nitrogen loss from the slash burned area averaged 4.6 lb/acre (5.2 kg/ha) compared with 0.14 lb/acre (0.16 kg/ha) from an undisturbed forest; 53 percent of the loss from the burned area was organic nitrogen attached to sediment in the stream water.

In more gentle topography where soil loss 'from erosion would normally be small, loss of nitrogen attached to sediment should be much less. As indicated by Grier and Cole's (1971) study which reported increased ion transport below the root zone following burning, dissolved chemicals in the stream water would be expected to increase roughly in proportion to the portion of the drainage burned. Buffer strips would have little influence on leached ions, and their value for controlling sediment losses has been questioned since most sediment is carried in stream channels which traverse buffer strips.

Removal of forest residues from the site would reduce the chemicals available on the area but would have only a minor influence on chemical water quality since the major portion of the nutrient capital is in the soil. Relative quantities of chemicals in various portions of a second-growth Douglas-fir forest are shown in table 1 (Cole et al. 1967). Most of the residue that could be removed would probably be made up of nonmerchantable bole wood and heavier branches which contain about 2 to 10 percent of the total capital of principal elements.

SUMMARY AND CONCLUSIONS

In general, forest residue reduction will influence the forest soil and water resources in proportion to the amount of soil disturbance created.

Drastic disturbance of litter and surface soil can lead to increased surface erosion leading to stream sedimentation. In some cases, natural and manmade residues have a beneficial onsite effect in combating erosion and preventing sediment from reaching streams. In steep topography, greater than 60- to 80-percent slope, removal of residues by any means that bares the soil leads to increased soil movement. A well-distributed cover of dead and live residues are necessary to control erosion, especially in single-grained soils, such as those from granitic parent material which are potentially highly erosive.

Residue treatment would not materially increase mass soil erosion unless machinery altered the slope by undercutting, as with tractor roads, or overloaded slopes with waste material.

Water yields should not be changed by residue treatments to any significant degree. Timing or distribution of peak flows could be altered by any operation that increased surface runoff primarily as a result of decreased infiltration following removal of litter down to mineral soil or by channeling water, as in skidroads.

In terms of water quality, the quantity of chemicals in streams evidently increases when rate of decomposition of residues exceeds the uptake by vegetation and the exchange capacity of the soil.

Fire creates the conditions most likely to release large quantities of chemicals that reach streams. Fire is also one of the agents most likely to expose the surface soil to erosion. Wildfires, which burn hottest, are the most damaging; controlled broadcast burns are less damaging to the soil surface but may release as much chemical as wildfires. Surface runoff and erosion can be greatly accelerated where infiltration is reduced through compaction of the surface soil. Compaction increases with increasing soil moisture content, with maximum compaction occurring midway between field capacity and the wilting point. Compaction can probably best be controlled by restricting the use of heavy machinery to avoid areas or times when compaction of soil would be expected, and restricting use of heavy equipment for residue treatment to existing road systems.

IMPLICATIONS FOR RESIDUE REDUCTION EQUIPMENT

From the soil-water standpoint, the most important features of equipment to be used in residue reduction should be those that prevent further disturbance of the soil surface. Except for equipment to be operated on existing road surfaces, residue reduction machinery should be lightweight and operated at a time that will not lead to compaction. On steep slopes, no machinery should be operated on the surface although it might be reas'onable to remove material by methods such as skyline, balloon, etc., that would leave litter and duff on the soil surfaces relatively undisturbed.

RESEARCH NEEDED

Soil and water research currently in progress will provide some information about residues and residue reduction even though very little is designed specifically to answer residue questions. Studies such as the IBP Coniferous Biome Ecosystem analysis will hopefully give us a'better understanding of the role of organic debris in nutrient cycling and water quality. If possible, research plans should be modified to develop new information on effects of residue and residue treatment. Several of the watershed studies by the Pacific Northwest Forest and Range Experiment Station include a variety of slash treatments such as clean yarding, broadcast burning, and no treatment. Specific effects of these treatments should be analyzed, although such effects are probably influenced by other activities on the watersheds. Consideration of new residue treatment methods should include evaluation of known effects on soil and water. When such information is not available, data should be collected to document specific effects of the treatment. For example, if chipping in the forest becomes an operational technique, additional laboratory and field research will be needed to determine to what degree it influences water quality.

ONGOING RESEARCH

The following are the principal studies related to effects of residues on soil stability and water yield and quality. Numerous other universities and State and Federal research organizations are also contributing to our knowledge.

International Biological Program
: Coniferous Biome Ecosystem analysis. Comprehensive study of western coniferous biome including movement of water and nutrients through the ecosystem, estimates of biomass, and terrestrial process studies (Franklin et a7 1972).

Pacific Northwest Forest and Range Experiment Station
: RWU 1602 - H.J. Andrews Experimental Forest, South Umpqua Experimental Forest, Fox Creek in Bull Run watershed, and Mount Hood National Forest - water yield, water quality, nutrient cycling and sedimentation, and soil

disturbance. Includes influence of burned and unburned logging residues on water quality.

RWU 1601 - (1) Entiat Experimental Forest - nutrient cycling, water yield, sedimentation following wildfire and revegetation. (2) High Ridge Evaluation Area, Umatilla Barometer watershed - Effects of three methods of forest harvesting on stream chemistry, sedimentation, water temperature, soil moisture, snow deposition, and wind behavior. Understory vegetation and physical and chemical properties of soil are being studied by RWU 1701.

Oregon State University, Forest Engineering, Corvallis.
Nutrient cycling, logging debris quantities and distribution, sedimentation, effect of finely divided slash on water quality.

University of Washington, School of Forestry, Seattle.
Nutrient cycling, sedimentation.

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FISH HABITAT

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ABSTRACT

Accumulation of residue in stream channels occurs naturally in Zarge amounts, particularly in old-growth forests. Residue volumes may triple in streams after timber is felled without buffer strips or other special measures designed to minimize accumulations. Although most of the Zarge residue may be yarded out of the stream, fine residue may remain at levels 'higher than before Zogging. Fine residues affect fish habitat by reducing dissoZved oxygen levels in surface water and by interfering with the circu-Zation of surface and intergravel water. Large residues affect fish habitat by influencing stream hydraulics, the stability of bed and banks during "flush-outs," and by blocking fish migration. Residue removal from streams must be done with care in order to minimize damage to fish habitat. Vegetation immediately adjacent to the stream is important to the aquatic habitat, influencing both water temperature and food supply for the fish. Protecting this streamside vegetation during Zogging and residue treatment is essential on valuable fish streams. The greatest single research need in the area of Zogging residue and fish habi-tat is the integration of studies concerned with Zogging method or residue treatment and those concerned with aquatic biology over a wide range of forest-stream-logging situations. Key areas of research are the impact of various Zogging methods on residue accumulation and on fish populations and the impact of residue accumulation on debris avalanches or "flush-outs."

Keywords: Fish habitat; stream management--debris dams, flushout, sediment, water quality, buffer strips.

INTRODUCTION

One of the most important natural resources of the Pacific Northwest is its fish. The region's anadromous fish runs, which include steelhead *(Salmo gairdneri)* and several species of salmon, provide both jobs and recreation for

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many people. Resident species, such as cutthroat trout *(Salmo clarki)*, also contribute to the region's fishery resource.

Small forest streams are important to productivity of the regional fishery. Many anadromous species use the small headwater streams for spawning. Some, including steelhead and coho salmon *(Oncorhynchus kisutch)*, depend upon small streams as rearing habitat for young fingerlings. These young fish spend 1 or more years in the small streams before migrating back to the sea. The quality of water in these small streams, therefore, plays a dominant role in the survival of these species.

These small streams, and the quality of their waters, are closely linked to the terrestrial ecosystem that they drain. Soils are highly porous, and slopes are efficiently drained with numerous small channels which connect the ridges to the main stream course. As a result, forest streams respond quickly to precipitation inputs. Topography is often steep in the forested watersheds of the Pacific Northwest, in addition to being highly dissected. Soils are often unstable and subject to mass soil movement and surface erosion, particularly after disturbance. Because of the terrain and rapid runoff characteristic of many Northwest watersheds, eroded materials quickly find their way into stream channels.

Logging residue may also reach stream channels quickly in this steep, highly dissected topography, particularly where precautions have not been taken to prevent its downslope movement. The zone immediately adjacent to the stream is often oversteepened by stream erosion. Trees felled in this zone generally end up in the channel, particularly since many trees lean strongly downslope. Smaller material may move toward the stream by creep.

Residue treatments using fire or machinery may affect the stream. The magnitude of the impact is determined by disturbance, as well as the physiographic and edaphic characteristics of the site.

The small stream, and the fish habitat that it represents, is a principal resource in most of the Coast and Cascade Ranges of the Pacific Northwest. It responds quickly to environmental changes and changes brought about by man. This chapter describes the impact of logging residue and residue treatment on the stream and its capability to produce fish.

CURRENT KNOWLEDGE

ACCUMULATION OF RESIDUE IN UNDISTURBED STREAMS

Residue accumulates naturally in undisturbed streams of the Pacific Northwest. Windthrow or mortality in trees adjacent to streams places large quantities of material in channels (fig. 1A). This material may either remain in place or be carried downstream during extreme runoff. Large log jams often found in undisturbed watersheds are created by high flows depositing logs behind some obstruction.

Residue accumulates in undisturbed streams over many years. Often residue is incorporated gradually into the streambed, forming small dams and the plunge pools which provide excellent habitat for fish.

A

Figure 1.—Stream channels in which forest residue has severely disrupted fish habitat (photos courtesy Dr. Henry A. Froehlich). Note that natural residues are no less a problem: A_, Natural residues in stream channel at an unlogged watershed; B_, logging residue in stream channel at logged watershed.

B

Little information is available about the accumulation of natural residue in stream channels. Lammel[2] described the natural residue accumulation in five small streams as part of a larger study of residue accumulation and logging. Total volume of natural residue in an area 15 ft (5 m) on either side of the stream varied from 343 to 1,400 ft^3 per 100 ft (31 to 130 m^3 per 100 m) of stream. The weight of this residue varied from 6 to 26 tons per 100 ft (19 to 77 metric tons per 100 m) of stream. About 10 percent of this residue was small, less than 4 inches (10 cm) in diameter. Fine residue, less than 1.2 inches (3 cm) in diameter, was about 2 percent of the total.

Lammel (see footnote 2) attributed part of the variation observed in the residue accumulating in channels to the nature of the slope above the channel and the time of storm events. Natural benches above stream channels restricted downward movement of residue from upper slopes. No such restriction was apparent on smooth slopes, and residue accumulation was higher in these streams. The timing of storms with respect to measurement date also influenced the values obtained. Flushing flows periodically clear residue from such streams.

Accumulation of leaf litter in woodland streams and lakes has always been of interest to aquatic biologists. Litter provides a substantial portion of the food energy input to these aquatic systems, and understanding the functioning of woodland streams requires some knowledge of how litter accumulates and degrades. Fisher and Likens (1972), for example, have shown that about 44 percent of the energy input to a small woodland stream came from litter which either fell or blew into the stream. Slack and Feltz (1968) measured 0.02 oz per ft^2 (5.3 g per m^2) per day of leaf accumulation in trays placed in a small woodland stream in Virginia during the leaf drop period. Hewlett (1969) reported an annual organic export of about 22 lb per acre (25 kg per ha) per year of dissolved and particulate organic material from a 60.1-acre (24.3-ha) watershed forested with hardwoods in Georgia. Hewlett noted that in hardwood forests, incised stream channels may efficiently trap hardwood leaves as they are moved across the forest floor by wind. Kaushik and Hynes (1971), in a review of foreign literature, note that the littoral of lakes receive 0.04-0.10 lb per ft^2 (200-500 g per m^2) per year. The leaf litter input to the Thames River has been estimated at 1.07 lb per ft (1.59 kg per m) of shoreline per year.

ACCUMULATION OF RESIDUE IN STREAMS BORDERED BY LOGGED AREAS

Large quantities of residue have been observed in streams that flow through clearcuts, particularly where logs have been felled and yarded across the stream (fig. 1B). Again, little information exists on the amount of residue accumulating after logging. Available data focus on the accumulation from some form of clearcutting; no information about the impact of partial cutting on residue accumulation seems to be available.

Lammel (see footnote 2) observed the accumulation of residue in five streams after felling and yarding of timber and compared the residue accumulation after each operation with the levels of natural residue observed before logging. Two streams had clearcuts on both sides, logs were yarded with a conventional

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[2] Richard Lammel. Natural debris and logging residue within the stream environment. M.S. thesis, Oregon State University, Corvallis, 49 p., 1973.

high-lead system, but a tree-pulling or cable-assist-felling technique was used to prevent trees from falling into the streams. A third stream had a clearcut on one side, a partial cut on the other, and a narrow--16.4-ft (5-m)--buffer strip that was not continuous along both sides of the stream. A fourth stream had a clearcut on only one side and a wide--164-ft (50-m)--buffer strip. The fifth stream was bordered by a conventional high-lead setting, no special felling techniques were used, and there was no buffer strip.

Total residue increased in all streams after timber was felled except the one with the wide buffer strip. Residue volume ranged from 1.2 times greater on the stream with narrow buffer strip to about **3.3** times greater on the stream bordered by a conventional high-lead setting without buffer strip. Most of this total residue was large, such as logs. Large residue that had accumulated naturally in these channels was yarded out with the commercial material. As a result, after logs were yarded total residue was reduced below natural levels in all streams except the one with the wide buffer. Residue volumes in this latter stream remained unchanged throughout.

Finely divided residue (less than 1 cm in diameter) was affected differently. No change in the volume of fine residue was observed in the channel protected by the wide buffer after felling or yarding of timber. Increases in fine residue were observed in all other streams after yarding and ranged from 1.1 times greater on the stream protected by the narrow buffer to **4.3** times greater in the stream bordered by a conventional high-lead setting. Volumes of fine residue after yarding were reduced to prefelling levels in one stream where cable-assist-felling methods were used; for the other cable-assist operation, fine residue volumes remained the same as before yarding. In the stream protected with the narrow buffer, fine residue volumes after yarding increased slightly over levels observed after felling. In the stream bordered by the conventional high-lead operation, fine residue volumes declined after yarding but were still three times higher than the prelogging level.

IMPACT OF RESIDUE ON FISH HABITAT IN STREAMS, LAKES, AND ESTUARIES

An excellent review of the impact of residue on fish habitat is presented by Narver (1971). The impact of residue on fish habitat seems to be most closely related to residue size. Small, or finely divided residue, may influence fish habitat by chemically degrading water quality. Large residue affects fish habitat through a direct, physical impact on stream channels.

Finely Divided Residue

Finely divided residue—such as leaves, needles, and small branch wood--contain inorganic nutrients, sugars, and polyphenolic compounds. Under natural conditions, relatively small amounts of residue enter the stream, and these compounds act in a positive way to add nutrients or energy to the aquatic ecosystem. Increased concentrations of these compounds in stream water may follow logging if fine residue accumulates in the channel.

The most significant impact of fine residue on fish habitat is its ability to reduce dissolved oxygen concentrations in stream water. Finely divided residue, particularly leaves and needles, may contain large amounts of biodegradable materials. These materials are readily utilized by aquatic micro-organisms as a source of energy. Oxygen is extracted from the stream by the micro-organisms as they degrade the material.

Residue may 'further influence dissolved oxygen concentration by restricting reaeration of oxygen-depleted water. Residue may obstruct small streams reducing velocity and turbulence, both significant factors in the reaeration process. Ponding and the exposure of stream surfaces that often follows logging may combine to increase stream temperature. Higher water temperature reduces the ability of stream water to hold dissolved oxygen.

The combination of biodegradation, reduced reaeration, and a lower saturation concentration can reduce dissolved oxygen concentrations to very low levels after logging. Hall and Lantz (1969) report that following clear-cutting in a small watershed in the Oregon Coast Ranges, large quantities of fine residue accumulated in limited sections of the stream. Dissolved oxygen levels, less than 1 p/m, were observed in these stretches; fish were unable to tolerate these conditions. The remainder of the stream was well below saturation but at levels sufficient to maintain fish. In an adjacent unlogged watershed, dissolved oxygen levels of 10 p/m were recorded. Holtje (1971) also observed oxygen depletion below a logging unit in another small Coast Range stream. In both instances, severe residue accumulation in the stream channel followed the logging.

Reduced dissolved oxygen levels have been observed in pools of small streams in Virginia after leaf fall in the autumn (Slack 1964, Slack and Feltz 1968). Levels below 1 p/m were recorded on both streams. Dead fish were observed in one of these streams. Situations such as this are highly improbable in west coast streams. Leaf fall usually occurs early in the rainy season, and the increased streamflow flushes litter from small channels.

Finely divided residue influences fish habitat in more subtle ways through its effect upon the food chain. Under natural conditions, residue falling into a stream or lake is attacked by fungi and micro-organisms including bacteria. Fisher and Likens (1972) report that about 44 percent of the total energy input to a small woodland stream came from litter. Hynes (1970) notes that most of the energy derived by primary consumers comes from this kind of residue. Communities of these consumers may act upon leaves and needles in the stream, each species degrading the material in a different way, making it available for further decomposition. Aquatic insects, such as stoneflies, and crustaceans depend upon fallen leaves for food. These animals, in turn, are utilized by fish. Chapman (1966) has shown that over half the energy obtained by coho salmon fingerlings in Oregon Coast Range streams is derived from terrestrial sources.

Predicting what impact high loadings of residue have on the food chain in small streams is not presently possible; nor can we predict the impact that might result after a rapid shift from a heavily loaded system to one in which natural residue levels from leaves and needles drop almost to zero, such as after clearcutting and burning. With exposure to sunlight, the stream's plant system may shift to a community of photosynthesizing plants until riparian vegetation returns; for fish populations, the meaning of this shift is not well understood. We also cannot predict what impact changes in stream water chemistry after clearcutting may have on the processing of residue materials by micro-organisms.

Finely divided residue may also affect fish habitat through its impact on spawning-gravel composition. Emergence of young salmonids from the gravel into the stream water above is strongly influenced by gravel porosity. Hall and Lantz (1969) have shown that pronounced reduction in survival occurs when gravels are clogged with fine sediments. Servizi et al. (1970) have shown that bark may produce a similar impact. Although leachates from the bark of Douglas-fir *(Pseudotsuga rnenziesii)*, lodgepole pine *(Pinus contorta)*, Engelmann spruce *(Picea engelmannii)*, and alpine fir *(Abies Zasiocarpa)* were not shown to be toxic to young fish, bark concentrations of 10 percent by volume of gravel significantly reduced survival due to blockage of intergravel water flow. Decaying bark also provided a medium for *Sphaerotilus*, a filamentous aquatic bacterium. Growths of this organism also filled the gravel pores, clogged the gill tissue of many fry, and caused severe mortality.

Large Residue

Large residue, such as logs or big limbs, may affect fish habitat by changing the stream hydraulics at the point of accumulation. Small amounts of residue may create a small waterfall with a plunge pool, adding to the diversity and productivity of the stream. Upstream, gravel and other sediment may accumulate. In some places, these sediments may be beneficial for spawning habitat; in others, such accumulations may bury or destroy good spawning sites. The result depends upon the type of pool formed behind the residue accumulation and the size of sediment deposited there.

Greater accumulations of large residue may act as a barrier to fish movement. This problem is particularly critical in the Northwest, where many of the fish species are migratory and the success of a spawning run may depend upon the fish reaching certain streams or stream reaches within some time limit. Log jams have long been of concern to managers of fisheries because of this impedance.

A phenomenon called a "flush-out" results from the accumulation of large residue in steep channels, either naturally or from logging activity in conjunction with high flows or mass soil movements. Flush-outs are particularly damaging to fish habitat. Channel banks and bed are often badly scoured as the wave of logs, mud, and water rapidly moves downstream. The wave seems to gain mass and momentum as it moves down the channel, picking up material from the channel as it proceeds. The productivity of stream channels near the origin of such events is often not significant; channels may be too steep to provide fish habitat or they may be dry for part of the year. The greatest damage generally occurs downstream as the flush-out moves into a productive area of the stream or into a larger stream course.

The effects of these mass movement events may last many years. Channels scoured to bedrock may not contain gravel for spawning or primary production for some time. Scoured banks add fine sediment to the stream much more readily than when vegetated. Finally, the gravel and other debris from the event add to the bedload and siltation of the channel in which they are deposited. Their residence time in the system, although never accurately documented, must be extremely long.

Flush-outs are frequent in many areas of the Northwest. They occur in both logged and unlogged watersheds. Like most other erosion phenomena, flush-outs are fairly infrequent under natural conditions and are associated with major storms or floods probably because, under natural conditions, residue accumulates slowly in channels. As a result, flush-outs pose an infrequent threat to fish habitat in undisturbed, watersheds. In the long interval between events, the habitat and fish population are able to recover. Only where the frequency of flush-outs increases as a result of logging and road construction may fish populations be seriously threatened. Also, although residue from man's activity may be small compared with the natural residue carried in major events, Rothacher and Glazebrook (1968) have observed that residue from logging may be like the top foot of floodwater which is more damaging than the rest.

Large residue which accumulates in small channels seems to have little effect upon chemical water quality. The only direct evidence of this comes from a study of log storage on water quality (Schaumburg 1970). Leachates from Douglas-fir, hemlock *(Tsuga heterophylla)*, and ponderosa pine *(Pinus ponderosa)* logs varied from nontoxic to slightly toxic. Biochemical oxygen demand (BOD) varied from about 0.0033 lb per ft^2 (1 g per m^2) to about 0.05 lb per ft^2 (15 g per m^2) of submerged log surface. Segments without bark generally produced leachates with a higher BOD than did those with bark. For most small streams typical of forest watersheds, large residue should pose no threat to chemical water quality, particularly if streams continue to be free flowing. Only a small portion of large material may be submerged during the critical low-flow period. Under such circumstances, the BOD from logs should be insufficient to cause significant water quality problems. The impact of large residue on the quality of water and fish habitat in lakes, large rivers, and estuaries depends, as Schaumburg (1970) points out, upon the quantity and type of material, how long this material remains in the water, and the character and flow of the water.

IMPACT OF RESIDUE TREATMENT ON FISH HABITAT

Few data describing the impact of residue treatment on fish habitat are available. Most treatments, such as piling, windrowing, chipping, etc., which keep residue out of the channel, should pose no problem for the aquatic system.

Residue accumulations in stream channels must be removed with care. Removing large accumulations generally requires machinery, such as tractors. Damage to stream banks and bed can be severe when such equipment is operated in the channel. Lantz (1971) notes that heavy equipment may cause channel changes, remove spawning gravel, and perhaps kill eggs in the gravel or small fish living in the stream. Much of the material in the stream channel is natural, as illustrated by Lammel's work (see footnote 2). Often, these natural residues have become incorporated into the banks and bed of the stream. Removing such natural residue during stream cleanup may seriously damage the channel--start a new sequence of channel erosion. In many cases, this natural residue provides excellent habitat for fish and should be left in place if possible. Lantz (1971) therefore recommends that fishery biologists be consulted to determine if residue removal from small streams is necessary after logging.

Removal of residue accumulations from stream channels by fire is **also** difficult. In many cases, the material is too wet to be burned completely. In other cases, the fire may be so intense that it either is difficult to control or severely burns the channel banks or area adjacent to the stream so that soil eroded from slopes will be immediately washed into the channel. This process is particularly evident when large accumulations of residue are burned in steep draws. The practice of yarding all residue for disposal by burning to a central point, located in a draw near the landing, can create a severe source of erosion. Fire in a small channel may also be directly lethal to fish. Hall and Lantz (1969) reported that water temperatures rose to lethal levels in a small section of a stream where a slash fire was confined in a narrow canyon.

Removing accumulated residue from the stream channel poses a hazard to fish habitat. The best treatment from a fish-habitat viewpoint is one that prevents the accumulation of residue in the channel. Directional or uphill felling of trees or the use of buffer strips to stop downslope movement of felled trees, although not usually thought of as residue treatments, should be considered as such for protection of 'fish habitat.

Rothacher and Lopushinsky (1974) have described impact of broadcast slash burning on erosion, sedimentation, and water chemistry. They note that intense fires that expose significant amounts of mineral soil may cause large increases in erosion and sedimentation. They also note that in one watershed study, concentrations of ammonia and manganese in the stream water exceeded permissible drinking water concentrations for 12 days after a slash fire. The manganese concentration, which reached 0.44 p/m, was less than the 1.0 p/m level considered harmful to aquatic life. The ammonia concentration, which reached 7.6 p/m, was probably at a toxic level (McKee and Wolf 1963).

The direct lethal impact of erosion and sedimentation on fish after severe slash fires is probably low (Rothacher and Lopushinsky 1974), and probably no lethal impact exists at concentrations of less than 20,000 p/m of suspended sediment (Cordone and Kelley 1961). Concentrations of 20,000 p/m from surface erosion are rare in small forest streams and persist only for very short periods.

The greatest impacts of sediment on fish are indirect and occur after deposition, influencing their habitat rather than being directly lethal during suspension in the flowing stream. Sediment indirectly influences fish populations, especially salmonids, by affecting the gravel environment where eggs are deposited. Siltation of spawning gravel is one of the most important impacts of erosion on fish habitat. Circulation of water through the gravels may be significantly reduced, thus lowering the dissolved oxygen concentration in the vicinity of eggs and increasing the concentration of carbon dioxide and toxic waste products normally borne away by subgravel water. After an extensive review of literature on the subject, Cordone and Kelley (1961) conclude that "...the effects of sediment upon alevins and especially eggs of salmonids can be and probably often is disastrous. Even moderate deposition is detrimental." Hall and Lantz (1969) found that fine sediments may reduce the survival of salmonid fry by blocking their emergence from the gravel to the surface water above.

Bottom organisms are also affected by sediment. The abundance of these organisms determines, in large measure, growth and condition of fish populations. Again, Cordone and Kelley (1961) reviewed the work of several authors which pointed out the importance of these organisms to fish populations and the reduction in bottom organism numbers with sedimentation. In some circumstances, sedimentation may change the species composition of the invertebrate community and reduce the available food supply for fish even though invertebrate biomass remains the same. Organisms which are available as food to fish and inhabit a gravel-bottomed stream may be replaced by burrowing organisms if gravels are covered by fine sediments. This latter group of organisms is generally less available to fish.

The impact of sedimentation on aquatic plants is much more difficult to determine. Much of the energy input into small streams is derived from the photosynthetic activity of lower plants, such as algae. Continued high turbidity may reduce the photosynthetic activity of aquatic plants by reducing the amount of light penetration in water. Measuring the impact of turbidity on aquatic plants is difficult; very little research has been done on this aspect of sediment concentration and stream ecology.

Turbidity is likely to be less of a problem for primary productivity in small mountain streams than is sedimentation. High turbidities usually occur only during winter months when rainfall and .runoff are high. Even on severely altered watersheds, stream turbidities are generally low during summer months and between winter storms (Brown and Krygier 1971). Sedimentation, on the other hand, may reduce primary productivity by burying stream gravels, the growing site for most of the algae in small streams. Sedimentation such as this is likely to be more severe on streams with low slope.

In summary, burning as a residue treatment has the potential for affecting fish habitat if serious erosion ensues. The impact is likely to be subtle--not directly evident as a fish kill, for example, but one which may influence fish numbers, condition, and growth through its effect upon the spawning environment and the aquatic food chain organisms.

Residue treatments, such as removal from stream channels or disposal by burning, may influence fish habitat if these treatments affect the vegetation near the stream channel. This vegetation includes not only trees but also riparian brush such as salmonberry *(Rubus spectabilis)* and vine maple *(Acer circinatwn)*. Streamside vegetation provides shade, essential for keeping small stream temperatures at acceptable levels. Large temperature changes--12°-25° F (6.7°-11.4° C)--have been measured after riparian vegetation was removed by logging and slash burning, exposing small streams to sunlight (Brown and Krygier 1970, Levno and Rothacher 1967). Removing streamside vegetation may also reduce the number of insects available to fish. Insect drop from overhanging vegetation is an important source of food for fish. Insect production from the stream is also influenced by water temperature. Only preliminary information is now available, but studies in the Oregon Coast Ranges indicate a less diverse population of insects in a stream draining a clearcut watershed than in one draining an adjacent unlogged watershed.3/ This means that the food source for fish may be less stabile in the clearcut watershed. Thus, it is evident that removal of streamside vegetation should be avoided on valuable fish streams.

Chipped residue, if allowed to accumulate in stream channels, would probably act similarly to fine logging residue, decreasing dissolved oxygen.

CONCLUSIONS

Several conclusions about residue and residue treatment and its impact on fish habitat can be drawn from our current knowledge of the problem;

3/ Unpublished data, Oregon Wildlife Commission, Corvallis, Oregon.

1. The accumulation of residue in stream channels occurs naturally in large amounts, particularly in old-growth forests.

2. After timber is felled, residue volumes may triple in streams with no buffer strips or other special measures such as cable-assisted felling designed to minimize accumulations. Although most of the large residue may be yarded out of the stream, fine residue volumes may remain at levels higher than before logging.

3. Fine residues affect fish habitat by reducing dissolved oxygen levels in surface water and by interfering with the circulation of surface and intergravel water.

4. Large residue affects fish habitat by influencing stream hydraulics, the stability of bed and banks during "flush-outs," and by blocking fish migration.

5. Residue must be removed from streams with care to minimize damage to fish habitat. If done improperly, mechanical removal of residue or burning of residue accumulations in stream channels may damage stream banks and bed, adding sediment to the stream.

6. Vegetation immediately adjacent to the stream is an important part of the aquatic habitat, influencing both water temperature and food supply for the fish. Protecting this streamside vegetation during logging and residue treatment is essential for valuable fish streams.

In view of these conclusions, the following recommendations are made about current practices:

1. Buffer strips or special felling techniques should be used to minimize debris accumulation in valuable streams during logging.

2. Removing accumulations of large residue from steep channels and ravines should be continued as a means of limiting "flush-outs."

3. Burning stream channels and ravines to eliminate residue accumulations should be done with caution and only as a last resort.

4. Hardwoods and other streamside vegetation should be protected as a means of controlling water temperature and channel damage during logging and residue treatment or removal.

RESEARCH UNDERWAY

A variety of research projects that focus on some aspect of residue and its impact on the aquatic environment are underway in the Pacific Northwest. These studies range from fundamental research on residue degradation by aquatic organisms to research seeking to quantify the residue accumulation in streams, produced by several logging techniques.

Residue breakdown by aquatic bacteria and the utilization of resulting nutrients by algae, insects, and fish are being studied by the Department of

Fisheries and Wildlife, Oregon State University, Corvallis. This project is sponsored by the National Science Foundation's International Biological Program. Carbon cycling in the aquatic community of a small forest stream in the Western Cascades will be studied, using radioactively tagged carbon. Changes in the carbon cycling process after clearcut logging on this small stream will be observed.

The effect of finely divided logging debris on dissolved oxygen is being studied at Oregon State University as part of the Department of Forest Engineering's logging impacts research. The study, sponsored by the U.S. Forest Service, will quantify the biochemical oxygen demand of Douglas-fir, hemlock, and alder *(Alnus rubra)* leaves and branch wood. Toxicity to fish and chemical composition of extracts from these materials will also be determined. The goal of this research is to prepare a predictive model for assessing the impact on dissolved oxygen of logging residue accumulation in streams.

A second study, also in the Department of Forest Engineering, will investigate the process by which organic material is incorporated into the gravel bed of small streams and the residence time of this material in the gravel. Coupled with the BOD study, this work should enable inferences to be made about the long-term effects of residue on the quality of water in the subsurface environment.

Quantifying the amount of residue, both natural and man-caused, which accumulates in streams is the objective of a third study of the Department of Forest Engineering at Oregon State University. Lammel's work (see footnote 2) is a part of this study. The study, which includes 13 streams, will follow residue accumulation before and after felling of trees, after yarding, and after cleanup on several types of logging operations. This study is closely linked to the other work in the Department of Forest Engineering and the Department of Fisheries and Wildlife and will provide excellent data for interpreting the results of these more fundamental studies.

Two projects dealing with residues appear in the Water Resources Research Catalog, Volume 6, 1970, published by the Office of Water Resources Research. One project, Limnological Effects of Organic Watershed Litter, is being conducted by Colorado State University. The project focuses on long-term bioassays of fish and invertebrates to determine subacute effects of litter leachates on survival, growth, and larval development. The other project, Degradation of Riparian Leaves and the Recycling of Released Nutrients in a Stream Ecosystem, is located at the University of Louisville. The study follows leaf degradation and its impact on a stream over a 4-month period.

A similar project, newly funded by the National Science Foundation, is being conducted at Michigan State University. The project, Woodland Stream Ecosystems, will determine the role of dissolved and particulate organic matter in stream ecosystems; this is probably the most intensive work on stream ecosystems now underway in the United States.

The Hubbard Brook Ecosystem study in New Hampshire, also sponsored by NSF, continues to provide excellent information on the functioning of small streams in northern hardwood forests in both natural and logged situations. This research program is conducted by several eastern universities and the Forest Service.

RESEARCH NEEDED

The greatest single research need in the area of logging residue and fish habitat is the integration of physically and biologically oriented studies over a wide range of forest-stream-logging situations. Research on comparable residue treatments, for example, must consider the aquatic portion of the watershed if a full evaluation of different residue treatment systems is to be made. Similarly, aquatic studies on residue loadings in streams are not very meaningful unless they can be interpreted as to the forest type and the physical and economic limitations of the logging system used. Evaluation of the impact of logging residue on the aquatic environment will require some highly sophisticated, as well as integrated, research. Understanding the impact of residue and residue treatments on fish habitat requires more than simple observation--such as fish number. The response of the entire aquatic ecosystem must be understood if the ultimate impact upon fish is to be discovered. With this need for integrated research in mind, several residue problems require immediate investigation.

Some of the greatest damage to streams and fish habitat results when avalanches of residue occur in steep, often ephemeral stream channels. Several questions bearing on this and related problems must be answered.

1. What is the relationship between channel characteristics including slope, shape, and condition of bottom, mass or volume of residue in the channel, and the frequency of debris avalanches or flush-outs?
2. What criteria can we use to predict the relative hazard caused by residue in a given channel? How can the impact of logging procedures be predicted and fully evaluated?
3. What is the impact of periodic debris avalanches on the aquatic habitat at the site of occurrence and downstream?
4. What is the recovery time of the channel and aquatic system after such events?
5. What corrective measures can be devised to hasten recovery of a damaged stream and what are their comparative costs?
6. In what situations should natural and logging residue be removed or left in the stream? What are the safest and least costly methods of removal?
7. What logging procedures can be used to prevent residue accumulation in the channels? What are the relative costs?

The effects of residue on fish habitat may be better understood when the foregoing questions are answered, but the land manager will still have the task of evaluating the alternative courses of action. The task is made complex by the many combinations of uses possible on most forest lands and the fact that many of these uses are often conflicting.

Water, the habitat for fish, is also a valuable resource for recreation, industry, power production, and many other uses. The timber and associated nontimber resources often require management measures not always compatible with the most favorable fish habitat. Thus, the ultimate answer to the residue-fish habitat problem will come when trade offs in resource values and production costs can be described. Then the land manager can select the goals in resource production he thinks society wants, with some knowledge of gains and sacrifices in each segment of the forest ecosystem.

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AIR QUALITY INFLUENCES

Owen P. Cramer

ABSTRACT

Fire has always been an integra2 part of the forest environment with destructiveness and smoke from wildfire directly proportional to the accumulation of flammable residue. Amount of smoke from prescribed burning is inversely reZated to the compZeteness of combustion which varies greatly with fuel, temperature, arrangement, moisture, and air supply. Emission characteristics of startup, full fire, and die-down stages are discussed as are effects of different fuel arrangements and burning procedures. Convective column and smoke plume behavior are affected by weather factors as well as by fire size and intensity. Though a local excessive concentration of forest smoke may occur temporarily, on a global basis removal mechanisms are keeping pace with all components except CO_2 which is slowly and steadily increasing. Air pollution nuisance from forestry prescribed burning can be minimized by use of a smoke management system that matches smoke production to atmospheric dispersion conditions. The present trend of increasing accumulation of forest residue under a fire exclusion policy can only Zead to increasing conflagrations and attendant severe smoke episodes. Management of the air resource must not be divorced from management of other resources that make up the forest environment.

Keywords: Air pollution--forest fire smoke, smoke management, forest emissions; air management.

THE AGE OF AWARENESS

The minor components of the atmosphere or any portion thereof are no longer taken for granted, particularly if they are visible and man-related. There is good reason why man's contributions to the air need to be examined.

Through the years, air pollution episodes have taken many lives, and a steady environment of polluted air has shortened many others. But these conditions have occurred where heavily populated areas were also heavy producers of sulfur dioxide and other byproducts of manufacturing or heating with sulfur-containing fuels. Even then, emergency conditions might have been avoided had it not been for man's penchant for concentrating his population and manufacturing in valleys or basins. This is important because all the notorious manmade air pollution episodes in history are phenomena of the lower layers of air--the lower 4,000 feet (1,219 m) at most, but more likely, the lower 1,000 feet (305 m), and usually in a valley or basin.

The air is normally stratified, particularly so at night; and the pollution episodes occur when the stratification is extreme for several days without appreciable wind. In these situations, emissions do not rise and mix with upper layers but are trapped in increasing concentration in the lower layers.

People still concentrate in valleys and basins where they evaluate air pollution severity in proportion to its obstruction of visibility. Occasionally, they also become aware of odor, bye-stinging, effects on plants, soiling, and even irritation of the respiratory system. Though these effects are often blamed on nonspecified "air pollution," they are actually due to specific chemicals and combinations thereof that incidentally may or may not have any relation to visible components of air pollution. And, in particular, these symptoms may or may not be related to the emissions from pyrolysis or combustion of forest-type fuels. We will examine more closely in this paper the impact of forests on atmospheric purity and the impact of residue and its treatment on ambient air quality.

Recognition of air pollution as an undesirable phenomenon has stimulated many concerns. One is the possibility that man is changing the natural balance of substances in the atmosphere and will thereby bring about serious changes in the world's climates (Bryson 1968). A great proliferation of State and Federal laws and regulations has appeared since the mid-1950's, aimed at reversing the trend of increasing indiscriminate disposal into the atmosphere. The coincident increase in attention to the environment and the popular discovery of the long known science of ecology have been accompanied by reiteration by ecologists that fire has been an essential factor in the development and maintenance of certain species and forest ecosystems (Weaver 1974, Mutch 1970, Heinselman 1970). Finally, there is considerable interest in learning the identity and characteristics of products released from the combustion of forest fuels and similar waste wood.

TRENDS IN ATMOSPHERIC COMPONENTS

The increased attention given air pollution in recent years would seem to imply that air quality must be considerably worse than it used to be. In checking this, one must carefully distinguish between strictly local air quality and composition of the entire atmosphere. Measurements of the general atmosphere indicate a trend in only one component--CO_2. Authors agree that the concentration of CO_2 has increased 0.7 part per million (p/m) per year and that the present concentration is about 322 p/m (Machta 1972), up from about 290 p/m in 1880 (Machta et al. 1969). Though CO_2 is a major product of combustion of cellulose materials (more than 1½ tons per ton of woody fuel (Hall 1972)), the increase is generally attributed to fossil fuel burning. But all of man's activities contribute only 0.7 percent as much CO_2 as is estimated to come from natural sources.

Suspended particulate is apparently also increasing, but thus far, more on a latitudinal rather than global scale. Whereas no increase has been noted in 60 years in the tradewind belt as measured on Mauna Loa (Machta 1972), Soviet data indicate increasing turbidity after 1940. Aerosol (very fine particulate) was found to have doubled over the North Atlantic in the past 60 years, although no change was detectable over 90 percent of the oceanic regions (Cobb 1973). The increase in particulate, estimated at 30 percent per decade (Lovelock 1971), appears to be concentrated in the heavily populated and industrialized North Temperate Zone.

Important though global trends may be, they are generally obscured by variations in weather at the local level. CO_2 concentration, for example, was found to be subject to overriding fluctuations in natural sources and more closely related to weather conditions than to urban area pollution (Clarke and Faoro 1966). Apparent changes in emissions are sometimes presumed on the basis of observed changes in local concentration. But local concentration and dispersion are dominated by weather conditions, e.g., days with calm wind and stable air vs. windy days with deep instability. The variability of weather from one short sampling period to another and from year to year is so great that no certain conclusions can be reached about change in amount of emissions without allowing for the influence of weather variables (Schmidt and Velds 1969).

The local concentrations of various kinds of contaminants are of immediate concern. Concentrations depend greatly upon weather conditions that cause emissions either to quickly disperse through a great volume of air, to accumulate near their source, or to move to some other place where they may add to local concentrations, be removed by natural processes, or undergo change.

The effects of forest emissions on air quality are varied. Emissions from the burning of forest fuels include the visible fine particulates of smoke and CO_2, which may add minute fractions to global amounts; but it is at the local level that smoke is of greatest concern. The living forest also emits CO_2 and other substances often considered pollutants when released by man. These include the photochemically reactive terpenes which are chemically similar to (and some more reactive than) important olefins in auto exhaust (Westberg and Rasmussen 1972). In total, the terpenes are much more plentiful though in less concentration locally (Robinson and Robbins 1969). The decaying materials on the forest floor emit CO_2, methane and other hydrocarbons, and ammonia. On the other side of the ledger, CO_2 is taken up in photosynthesis in forming wood and other plant materials at a rate that increases with the concentration of the gas. A recent development is that soil bacteria and fungi are a major sink for CO and other contaminants (Inman et al. 1971). Though this may become an important consideration in planning open space in pollution problem areas, our immediate concern is with emissions related to forest residues.

As important as trends in concentrations of various substances in the air is the trend of increasing knowledge of what substances go into the air and what becomes of these substances. More than half the aerosol presently in the lower atmosphere comes from secondary processes--chemical reactions in the gas phase between such components as volatile hydrocarbons, NO, NH_3, H_2S, SO_2, and O_3. Man contributes now about 6 percent of the total aerosol (Hidy and Brock 1970).

LEGAL REQUIREMENTS

Fire has always been a component of the forest environment. Foresters have substituted prescribed fire for some wildfire. But smoke from prescribed fire is from man's activities and, hence, becomes potential pollution and subject to legal restrictions.

In the haste to quickly reverse the deterioration of certain portions of the environment in problem areas, lawmakers developed a strategy for rapid action. What appeared to be the most serious conditions were tackled first. New laws were passed to carry out single purpose objectives--clean up water (Federal Water Pollution Control Act 1956, 1970); clean up air (Clean Air Act 1965, 1970); clean up solid waste (Solid Waste Disposal Act 1965, 1970); clean up the environment (National Environmental Policy Act, 1970). The resulting agencies became programs in the Environmental Protection Agency in 1971.

Existing laws with broad environmental assignments received less emphasis. The directive of the Multiple Use-Sustained Yield Act (1960) for "management of all the various renewable surface resources of the national forests so that they are utilized in the combination that will best meet the needs of the American people" seemed to have been eclipsed by the emphasis given to single resources. The purpose of the Federal Water Pollution Control Act of 1956 as amended in 1970 is "to enhance the quality and value of our water resources and to establish a national policy for the prevention, control, and abatement of water pollution." Purpose of the 1972 amendments was similar.

The purpose of the Clean Air Act is "to protect and enhance the quality of the Nation's air resources so as to promote the public health and welfare and the productive capacity of its population.. .."

The National Environmental Policy Act (NEPA), expressing concern for the entire environment, establishes the responsibility of the Federal Government to "assure...healthful, productive, and esthetically and culturally pleasing surroundings," "attain the widest range of beneficial uses of the environment without degradation," and "enhance the quality of renewable resources.. ." as supplementary to policies and goals "set forth in existing authorizations of Federal agencies." But the resulting action programs seem to have been aimed primarily at air and water quality.

Since the air resource and water resource are integral parts of the forest environment, management of the forest environment must be a balanced procedure that provides for enhancement of all the resources--soil, forests, wildlife, forage, water, and air "in the combination that will best meet the needs of the American people." This means that air resource management decisions must be a part of overall environmental planning. Such an approach still requires, however, assurance of air quality such "as to promote the public health and welfare." In addition, the NEPA says, and the Supreme Court has held (U.S. Environmental Protection Agency 1973), that the quality of the environment and of the air is not to be degraded. Several guidelines are provided:

1. National ambient ai'r quality standards indicate permissible maximum levels of specified pollutants such as nitrogen oxides, sulfur dioxide, photochemical oxidants, carbon monoxide, hydrocarbons, and particulates.

2. In addition, the nondegradation principle says that the air quality may not be worse than it is now even if it is considerably more pure than the ambient air standards permit.

3. States and local air quality control districts have the responsibility of translating the national ambient air quality standards into emission standards and of promulgating plans for achieving and enforcing the ambient air standards. Federal agencies are expected to "comply with Federal, State, interstate, and local requirements respecting control and abatement of air pollution" (Sec. 118, Clean Air Act of 1970).

4. At each step from Federal standards toward local regulations, requirements may be increasingly stringent except as otherwise provided for.

Traces of a substance somewhere in the atmosphere and pollution caused by that substance are different things. In this article we consider pollution as the presence of a substance in concentrations that produce undesirable effects on man and his environment. These effects and concentrations have been described in a series of "criteria" documents by the predecessors of the Environmental Protection Agency (EPA) for the more important pollutants (U.S. National Air Pollution Control Administration 1969). Toxic substances have been identified for which control measures are required. It would seem that a condition of pollution requires the presence of the offending substances in proximity to people, plants, animals, or materials, or where atmospheric transparency is needed, in a concentration and for a duration that actually tends to produce the undesirable effects. Because of the profusion of emission sources in a metropolitan area and the frequent weather conditions that cause these emissions to accumulate close to their sources, air pollution there is of real significance. Advection of polluting substances in significant quantity from source areas into other pollution-prone or pollution-sensitive areas does occur. But the mere presence of a substance with pollution potential somewhere in the atmosphere but of insufficient concentration or duration or in a location or situation that precludes any of the undesirable effects from occurring cannot reasonably be classed as pollution. It may, of course, temporarily degrade the quality of some portion of the atmosphere; but this seems often to be an academic question with limited practical application to environmental effects or management.

There appear to be some omissions from our present legal approach to eliminating or minimizing forest smoke in the environment. For one, the possibility of trade offs with other environmental factors has been neglected. An environmental solution is not required, only an air quality solution. Ineffective against wildfire, prohibition of forest smoke might better be redirected toward achieving a minimum total production of smoke from wildfire plus prescribed fire, and particularly toward minimum exposure of sensitive areas to concentrations of such smoke. Designation of ambient air quality standards without defining either ***ambient*** or sampling designs to be used in determining ambient conditions has left the question of smoke concentration in nonpopulated areas or in layers above the surface in limbo. Further legal considerations would stem from designation of each forestry burn as a ***new** source*. Recent efforts to establish a base for measuring ***degradation*** of air quality, especially with respect to particulate from new sources (U.S. Environmental Protection Agency 1973) without consideration of smoke from either forest wildfires or prescribed burning, raise additional questions about the legal aspects of smoke from forestry uses of fire.

Forestry uses of fire are classified as open burning from nonpoint sources. and, along with agricultural burning, have been given some degree of exemption from the usual prohibitions against open burning. These are temporary exemptions because open burning is generally considered by air quality protection agencies to be an unacceptable procedure regardless of purpose, fuel, method, or location.

Inevitably, smoke from wildfire and prescribed fire will continue to be of potential importance to local air quality. We do have some control over the smoke produced by such fires--over wildfire smoke through hazard reduction techniques and suppression efforts, and **over** prescribed fire smoke by smoke management. Since foresters can have considerable influence on smoke from both sources, examining the effects of such smoke on the environment, of which air is one part, is highly appropriate.

FIRE IN THE ENVIRONMENT

Fire has been a natural, often destructive, and in many forest.types a common component of the forest environment. Fire has determined the present species composition of natural forest types and was most likely essential in the actual development of individual tree species (Mutch 1970), particularly those represented in the fire climax types such as Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco), ponderosa pine *(Pinus ponderosa* Dougl. ex Loud.), and lodgepole pine *(Pinus eontorta* Dougl. ex Loud.).

Natural ponderosa pine forests, for example, experienced light periodic fires, probably started by lightning, every 4-18 years as indicated by old stump scars (Hall 1971, Weaver 1974). This developed the characteristically open, many-aged forest with little potential for destructive fire. With the exclusion of fire, young stands are now typically even-aged, often stagnated, and they constitute a serious fire hazard both before and after thinning. Species composition is changing toward more tolerant, less fire resistant species. Successful management of ponderosa pine may depend on restoring fire, in the form of periodic light underburning, as'a routine part of the silvical routine (Weaver 1974).

In western Oregon where lightning is less frequent, Douglas-fir forests date from large, severe fires that killed the preceding forests. Most old-growth stands carry charred bark as evidence of lesser fires. But as the stand goes into overmaturity, the dead material on the ground accumulates, and the understory space is taken over by more shade-tolerant species. The fuel accumulates toward the day of another destructive fire and a new generation of Douglas-fir. The forester tries to prevent the destructive fire and often uses fire to remove the excess accumulation of unutilizable woody fuel. In younger, healthy stands under management, mortality is likely to be salvaged as it occurs, leaving comparatively little residue at the time of final harvest.

Silvical practices for management of Douglas-fir duplicate some of the results of wildfire without the destruction and risk. Old-growth stands are logged, opening the surface to sunlight; and the excess residue is removed, sometimes by burning, to provide full exposure for planted or natural reproduction. On hot, dry sites where less than full exposure is desired, the shelterwood harvest-regeneration system is used; a portion of the overstory is left to provide partial shade until the new stand is established, simulating the moving shade canopy of the fire-killed stand.

Wildfire is still naturally present in the forest environment, despite man's endeavors to remove it. Over the last 50 years, wildfire acreage has definitely decreased in all forest areas. This trend has been especially dramatic in the South where over 2,000,000 acres (809,400 ha) of forest land are routinely burned by prescription each year (Hough 1973). In Pacific Northwest National Forests, wildfire acreage decreased from 1910 to 1940. Compared with 175,000 acres (70,822 ha) of forest burned in an average fire season around 1910, the figure since 1940 has averaged closer to 20,000 acres (8,094 ha) per year. Though fuel availability is obviously important, many other factors including fire detection, speed and effectiveness of initial attack, road accessibility, etc. make a statistical evaluation of the effect of slash disposal on size of wildfire uncertain. However, many of the people engaged in wildfire suppression have often reported that control lines are easily held, spot fires are readily contained, and spread and severity of burn are much less where hazard reduction activities such as slash disposal have been completed. In untreated areas, spread has been great and control efforts next to impossible. In recent years, some combinations of extremely dry weather periods and dry lightning storms have resulted in large acreages of wildfire in unabated problem fuels.

In the Pacific Northwest, use of broadcast burning to dispose of logging slash has been decreasing for some time, and use of the piling and burning method has increased. A greater increase, however, has been in acreage of unabated slash receiving extra protection in lieu of treatment, particularly in partial cut stands which are also on the increase (table 1). A factor in the decrease in burning has been air quality requirements that eliminate many potential burning days because of inadequate smoke dispersion (Cramer and Westwood 1970). As a result, total hazard from fuels remaining after logging has been increasing. Fuels in forest areas naturally subjected to periodic burning, and from which fire has been excluded, are also increasing. Although the average annual amount of smoke from forest sources, wildfire and prescribed fire combined, is far below what it was in the early 1900's, with fuels on the increase and the usual methods for abating them severely limited, the chances for smoke episodes from large wildfires are growing. This trend may well lead to actual increases in total smoke from forest sources in addition to increasing damage of more permanent nature to other resources, the inevitable result of wildfire.

Table 1.--*Comparison between 1963 and 1972*[a/] *areas of slash created and slash treatment on National Forests of the Pacific Northwest Region*

(In thousand acres)

Method	1963	1972
Clearcut	57	63
Partial cut	284	549
Broadcast burn	45	26
Pile and burn	0	87
Receiving extra protection:		
Clearcut	0	36
Partial cut	512	912

a/ From "Annual Slash Status Report," R6-5150-2, USDA Forest Service, Region 6.

Though fire is being used less as a routine tool for eliminating excessive residue, especially by broadcast burning, it is still essential for residue removal where there is no satisfactory alternative. The environmental trade off is of a preventive nature. Under a policy of residue management, the total fuel burned and smoke produced over a long period of time will be reduced. The area burned by destructive wildfire will certainly be less, and the smoke from prescribed burning would be produced only when dispersion conditions are favorable.

Effectiveness of fire hazard abatement in reducing total smoke emissions from forest sources cannot be fully determined in terms of air quality in 1 or 2 or even 5 years. Weather is highly variable from year to year, and the factors that determine trajectories, accumulation, or dispersion of smoke are no exception. Factors controlling the occurrence, spread, and duration of forest fires--such as lightning storms, drought, and periods of strong dry winds--also vary greatly from year to year. Forest residue management policies will have no effect on smoke from wildfires during damp, minimum severity, fire seasons. In years with severe fire weather, the effects of residue management on all the environmental resources will have the greatest impact; but those years, which are really what fire suppression planning and hazard reduction are all about, come at irregular intervals as far apart as 10 years. The real effectiveness of fire hazard abatement can only be determined if the effect of weather is first eliminated. As was done for determining the trend in number of man-caused fires (Cramer 1959), fire season weather severity indexes need to be used to detect changes in pattern of fire occurrence that may be caused by changing forest residue management policy. Indexes based on pertinent weather factors are also needed for detecting any difference in air quality from what might normally be expected in a given locality for any given weather condition.

NONDEGRADATION

Nondegradation may be viewed from an absolute or relative standpoint. From the absolute standpoint, degradation means addition of any impurity regardless of amount. This would seem to say that the atmosphere is pure, but this is not the case. In addition to oxygen and nitrogen, it includes a mixture of varying amounts of many substances. Natural sources such as plant and animal respiration and decay, lightning and lightning fires, duststorms, and volcanoes put many more times the particulate, hydrocarbons, CO, CO_2, sulfur compounds, NO_x, and other chemicals into the atmosphere than man does. And these all have their characteristic residence times and removal mechanisms (Robinson and Robbins 1969). The atmosphere has great capacity to dispose of these materials, though local concentration may be temporarily excessive. This would imply that concern about absolute degradation becomes rather academic.

Relative degradation requires a base for comparison. Atmospheric purity varies diurnally, from day to day, and year to year as a result of natural factors, primarily weather. Degradation can only be judged against a base from which these fluctuations have been eliminated such as by long-term averages. With respect to smoke from forest areas, selection of the base involves some choices:

1. The condition that existed before the white man. In the Pacific Northwest, there was much more burning than today. The entire ponderosa pine region burned every 4-18 years from lightning fires (Weaver 1974). Indians used fire annually to keep the main west-side valleys open. Occasional tremendous forest fires, described in early day accounts (Morris 1934) and determined by ages of present stands, occurred west of the Cascades.

2. The period of increasing intensity of forest fire control--1912-40. A great but decreasing number of large forest fires occurred. Hazard abatement fires became common after logging. All accidental and lightning fires were extinguished as rapidly as possible. Where forest fuels had been reduced by periodic fires, they began to accumulate. Though number of man-caused fires increased with increasing forest use, total acreage burned decreased.

3. Intensive fire suppression and substitution of increased protection for hazard reduction (1940 to the present). Total acreage burned remained low except in years with bad fire weather. Large fires, mostly from lightning, burned destructively in areas of fuel accumulation. Acreage burned by wildfires may be increasing. Acreage burned in broadcast burning greatly decreased; use of pile burning greatly increased; extra protection of unabated hazard greatly .increased.

Selection of a particular year as the basis for judging degradation would be meaningless unless the relative fire danger were taken into account. Possibly a more important factor is the buildup of fuel which is likely to contribute to wildfire acreage and smoke regardless of (if not partly because of) air quality requirements. Fire control specialists and ecologists (Hall 1971, Wilson 1970, Weaver 1974) are recognizing that the effort to completely exclude fire from the forest has resulted in potential for increased fire and smoke.

A more rigid requirement for decreasing smoke from hazard reduction fires, before satisfactory alternatives to burning are available, is likely to further increase the number of destructive large fires. A better solution that would permit correction of the current management policy of withholding fire would be a broader policy of nondegradation of the total environment. Such a policy should reduce the forest fire hazard so as to achieve a balance of minimum total emission from prescribed fire and wildfire and minimum acreages of destructive wildfire and fuel complexes likely to support destructive wildfire. In the process of achieving and maintaining such a balance, any prescribed burning should be accomplished by techniques that minimize emissions, and through smoke management systems that minimize forest smoke contributions to actual air pollution.

WOOD WASTE AND COMBUSTION

Forest residues are composed of organic compounds, mainly cellulosic material, seemingly almost the perfect fuel since under complete combustion it converts into into H_2O and CO_2 with little else but mineral ash, nitrogen from living cells, and a trace of sulfur. This may nearly be accomplished in certain forced-draft open pit or bin incinerators. But in the process of nearly complete combustion, the temperature reaches levels at which nitrogen oxides, , primarily in the form of NO, are produced.

In nature, combustion is less complete (see Hall (1972) for a more complete discussion of' the composition and emissions of forest fuels). It consists of many chemical processes that may be interrupted at various stages, thus producing a great many products of partial combustion. Combustion is more complete with dry fuel burning well ventilated at a high temperature. Smoldering combustion without flame produces the most byproducts, including the most visible smoke.

There are many situations in forest management where it is desirable, if not necessary, to dispose of huge quantities of accumulated forest residue--material that, for various reasons, is unwanted. Nature's fate for this would be decay, which also produces emissions, or wildfire. To forest managers, decay is much too slow when large amounts are involved; and wildfire, usually under the most severe weather conditions, is not a solution but a very serious threat to the entire forest. Prescribed fire, an adaptation of a natural process, applied under carefully preselected conditions to accomplish the necessary job with least negative impact on the environment, is currently a necessary tool for removing excess forest residue in many situations. Though less has been burned in recent years, an estimated 10 million tons (907,200 metric tons) of logging residue were eliminated annually by burning in Oregon, Washington, and northern California in 1962-64. The Wenatchee lightning fires of 1970 consumed about half this amount in a 10-day period. The Tillamook fire, in a single afternoon in August 1933, produced emissions something like 2½ times the 1962-64 regional annual average slash disposal.

In contrast, prescribed burns are separated in time and space,, thereby providing a dilution factor. Additional' dilution at ground level downwind is provided by the equivalent tall stack effect of a strong convection column that often lifts a slash smoke plume 5,000 feet (1,524 m) or more. Dilution or even complete separation of smoke from surface receptors in smoke-sensitive areas is often provided by an initial difference in elevation of several thousand feet--an additional section on the tall stack effect.

In 10 Oregon and 5 Washington counties that extend into what the National Air Pollution Control Administration (NAPCA) calls the Willamette Valley Metropolitan Area, over 1,350,000 tons (1,224,720 metric tons) of logging slash burned in 1968, producing an estimated 6,780 tons (6,151 metric tons) of particulate, 43,400 tons (39,372 metric tons) of CO, 2,170 tons (1,969 metric tons) of hydrocarbons, and 1,340 tons (1,216 metric tons) of NO (Hoffman 1970), according to NAPCA's estimates. Nationally, forest combustion sources have been credited with 24 percent of the particulate emissions (Dieterich 1971). Smoke from combustion of forest residues definitely goes into the air--hopefully, we have a choice of producing it where, when, and how we choose or of accepting the unpredictable timing and additional destructiveness of wildfires.

EMISSIONS FROM DIFFERENT KINDS OF FUEL AND ARRANGEMENTS

Smoke from the use of fire in forestry has generally been called air pollution without benefit of discriminating analyses to determine just what wood smoke is composed of or what it may do as a pollutant. The same gross generalizations apply to fuel and burning technique. Many kinds of fuels are burned in a slash fire and a somewhat different group in wildfire. Each type of fuel is unique in chemical composition, size, shape, moisture, arrangements, pyrolysis products, and combustion characteristics and products. Individual fires are likely to be unique in composition of different fuels, temperature and heat energy generation rate, moisture and ventilation levels, fuel volume, combustion rate, and duration of various stages of fire from start to smoldering remnant. With these many variables, it is extremely unlikely that all smokes from some kind of fire burning in some kind of forest fuel will be similar. In Australia, Vines et al. (1971) found, for example, that the nature and size of smoke particulate "vary significantly from fire to fire and even time to time during one fire." To effect control over deleterious substances among smoke components, we need to know what is produced and by which combination of fuel and burning condition.

Complete combustion of most forest fuels would produce CO_2, water vapor, ash, heat, and minor traces of other gases, with probably no visible emissions. But complete combustion seldom takes place. As described by Hall (1972), forest fuels going into a fire will emit products by straight distillation, by pyrolysis or destructive distillation at higher temperatures, and by glowing combustion of the remaining charcoal. Some of the products of these processes burn and some do not. The resulting emissions are made up of the pyrolysis and distillation products and various combinations of their components in all degrees of oxidation--some in gaseous form, others condensed on carbon particles, some as vapors. According to Hall (1972), "To sum up these complex processes, the amounts of substances burned, escaping unchanged, or altered by heat and intermolecular reactions, or by partial oxidation, present infinite possibilities in the matter of final products."

Individual fuel components will contribute different kinds of chemicals in different proportions; Forest fuels vary in amounts of hydrocarbons, nitrogen in living cells, proportion of lignin and cellulose, etc. Hence, the fuel burned as well as the manner in which it is burned influences the chemicals emitted. Some prominent forest fuels with different chemical characteristics are:

Conifer duff	Grass	Dead sound wood:
Conifer needles	Herbs	Conifer
Conifer twigs	Brush	Hardwood
Conifer bark	Ferns	Hardwood and brush foliage
Rotted wood--brown	Moss and lichen	
Rotted wood--white		

FUEL EMISSIONS FROM LABORATORY TESTS

Of the many different kinds of fuels involved in forestry uses of fire, a mere few have had limited analyses from laboratory burning tests[1/] (Darley et al. 1966).

Similar values of 2.4 to 4.4 lb of hydrocarbon per ton (1.2 to 2.2 kg per metric ton) of fuel burned were reported for small samples of Douglas-fir, western redcedar (*Thuja plicata* Donn), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) slash (Fritschen et al. 1970). Darley et al. (see footnote 1) report particulate produced ranged from 11 to 17 lb per ton (5.5 to 8.5 kg per metric ton). In the laboratory fires, they were able to detect differences that indicated.head fires produce three times the particulate produced by backing fires. Grass fires produced 16 lb of particulate per ton (8 kg per metric ton). A smoldering fire in litter and duff was found to produce 3 to 10 times as much particulate as the same material aflame.

From the laboratory data, we know that the hotter the fire, the more complete the combustion; hence, the less particulate, hydrocarbon, and CO. Floisture decreases fire intensity, hence it increases the products of incomplete combustion. This implies that living foliage and small live twigs, brush, and herbaceous growth will produce more smoke, a fact of which most backyard burners are already aware. Dry fuels or hot fires burn more completely with less smoke.

When we know the products emitted by various fuels, we can designate the preparation of fuel and burning procedure that will involve the desired fuels and burn them as completely as possible. For example, piled materials can exclude

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1/ Ellis F. Darley, Harold H. Biswell, George Miller, and John Goss. Air pollution from forest and agricultural burning. Paper presented to Western States Section/The Combustion Institute, Seattle, Wash., 10 p., April 24-25, 1972.

the duff, herbs, brush, and rotted wood that would be burned by broadcast burning, or preparation might require all material over 4 inches (10 cm) in diameter to be piled and burned and small material to be crushed in place or chipped and scattered.

FUEL COMPLEXES IN THE FOREST

The forest is composed of a considerable assortment of fuels. In some kinds of fire, such as wildfire, they all burn, usually under comparatively dry conditions but with the inefficiency of a head fire burning under partially limited oxygen supply. This is demonstrated by the occasional spectacular explosions and huge sheets of flame that ignite smoke rich in pyrolysis products well above the ground over fast-moving wildfires. The wildfire also burns a large proportion of live foliage, small living twigs, herbaceous material, and the duff accumulation on the forest floor (Martin and Brackebusch 1974). Particulate emissions from the head of a wildfire in the South have been estimated at 58 lb per ton (29 kg per metric ton) of fuel consumed in comparison with 1 to 10 lb per ton (0.5 to 5 kg per metric ton) from prescribed fire.[2/] Emissions of CO and hydrocarbons would be expected to vary similarly.

Emissions from the various kinds of burns depend greatly on factors affecting the temperature of the burn. Duff or rotten wood by itself will burn slowly at a comparatively low temperature, with little flame, hence, with considerable smoke. If duff or rotten wood is part of a complex of fuels that generates higher temperatures, more of the pyrolysis products of the low temperature fuels will be consumed in the flames of other fuel components. The heavier concentrations of fuel are likely to produce less emission of incomplete combustion products per ton of fuel burned than are light amounts. Hence, large open piles are more efficient than a broadcast burn, and the broadcast slash burn more efficient than a light underburn or an agricultural field burn.

In prescribed burns, there are various combinations of fuels, depending on the type of burn and its objective. Any broadcast slash burn consists of a diverse mixture of hot-burning dry material , slow and inefficiently burning duff, dry resinous foliage, and a selection of green herbaceous, brush, and small tree materials. Some of the fuels are close to the ground and will not get optimum air supply. Burning is usually done when the soil beneath is damp and the adjacent forest areas are sufficiently damp to prevent rapid spread from any wayward embers. Hence, some of the fuel burned will be damp, and some of the fire will be comparatively cool depending on type, amount, and arrangement of fuel, and the efficiency of the combustion mixed. Since the usual broadcast burn is in heavy amounts of fuel, much of the incompletely burned emissions of cooler burning fuels will be further oxidized in the hotter combustion of other fuels.

Even less efficient combustion would be expected of the light prescribed underburn conducted to remove some of the excess undergrowth and residue accumulating on the forest floor. This type of burn is usually conducted when only part of the duff is dry enough to burn. It may be only hot enough to kill

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[2/] Robert W. Cooper. Trade-offs between smoke from wild and prescribed fires. International Symposium on Air Quality and Smoke from Urban and Forest Fires Proceedings, Ft. Collins, Colo., Oct. 23-26, 1973 (in preparation for publication by Committee on Fire Research, National Academy of Sciences, Washington, D.C.).

small trees up to a few inches in diameter and may not even consume brush. It will remove dry branches, concentrations of dead fallen stems, excess litter, and the top of the duff layer. A second burn, sometime later, will consume the then dry small trees and brush killed by the first fire, a layer off old stumps and logs, and the litter and dead branches added in the interim. The fire is slow moving, poorly ventilated, and often in fuel just barely dry enough to burn. Heat produced is low and the emissions undoubtedly high per ton of fuel.

At the other end of the scale is the fire produced by a method still undergoing field tests--the pit or portable bin incinerator with a high volume forced air supply. This kind of burning has the characteristics of a limited combustion chamber and ample air supply delivered by a blower. Combustion takes place in a pit or bin of approximate dimensions up to 10 by 10 by 40 feet (3 by 3 by 12 m). Forced draft from the top of one side is directed down and across the combustion chamber. The resulting fire is extremely hot and combustion efficient. Visible emissions are mostly limited to the startup period or the few seconds following the dumping of a load of fuel into the fire releasing a cloud of ashes and a few wisps of smoke. 'This type of burner is excellent for large fuels which it completely consumes, though it accepts any fuels and burns them rapidly and completely regardless of moisture content at a rate of 10-15 tons (9-13.5 metric tons) per hour. It is probably best adapted to special situations such as road construction where space and time are limited, or where holdover fire may be a risk, soil may be vulnerable to broadcast or piled burn, or where visible emissions preclude open burning. Its limitations include high cost, limited rate of burning, and suitable pit site or road for the mobile burner. Both versions also require yarding the residue to the burner, an operation that may be too costly or too damaging to other environmental components of some sites.

If fuel is insufficient to support a broadcast burn, it is usually piled. The process of piling, if properly done, eliminates duff except beneath the pile, and much of the other finer fuels which may become detached from larger material. Cat piling or windrowing includes most of the woody material. But quality of piles varies--soil in piles, as a result of improper technique or wrong equipment, causes prolonged smoldering and risk of holdover fire. Properly assembled clean piles burn more efficiently than a broadcast burn because of better ventilation, higher temperature generated by the greater concentration of fuel, and minimum amounts of green or smoldering-type fuels.

A recently added required alternative, yarding unutilized materia7 (YUM) assures greater cleanup of clearcut areas. All pieces larger than a certain minimum (e.g., 10 ft long and 10 inches in diameter or 3 m long and 25 cm in diameter) are yarded into a huge jackstrawed pile or deck. This pile may be burned sometime well into the rainy season when danger of spot fires from embers is nil. The pile consists of only the heavy wood fuels and, once started, will burn hot with considerably less visible emission than the same material broadcast burned. This procedure may not be desirable if the amount of fine material and brush remaining after YUMing still presents sufficient obstruction and hazard to require burning. Then broadcast burning without YUMing would be more appropriate.

SMOKE PRODUCTION CHARACTERISTICS

Besides varying in composition, smoke from forestry uses of fire also varies during the stages of any given burn. Since the fire that produces the smoke also produces heat, a convective column of rising hot gases usually forms over a fire, lifting the smoke above fire elevation in proportion to the fire's rate of energy release. At the top of the column or wherever the smoke loses its buoyancy, it drifts in response to air motions at that level. We will call the nonbuoyant smoke from a specific source, a *plume* (see later discussion). Prevailing weather conditions greatly influence column and plume behavior. These characteristics are of great importance in maintaining air quality while using fire.

STAGES OF SMOKE PRODUCTION

Although the smoke produced by any fire largely depends on what the fuel is, smoke production characteristics can be divided into startup, full fire, and die down periods. During the startup period, a much larger proportion of unburned distillation and pyrolysis products will be emitted directly without burning. The fire will be generally cool and the combustion inefficient. In heavy fuels, this stage is shortest.

In the full fire or mature stage, the fire, for its particular fuels, moisture, and arrangement, burns at maximum temperature and rate. The emissions will be least because combustion is most complete and the rate of energy production greatest.

In the final stage, the temperature is lower, flaming gives way to glowing combustion, and remaining fuels may produce a higher proportion of CO and a greater amount of unburned distillation products and particulates (see footnote 1). This stage is probably the most troublesome because most of the heat energy is gone, the emissions may accumulate or drift at fire elevation, and this stage in scattered heavy fuels may last longer than the other two.

Size of fire, particularly with piled fuels, is also important in determining relative efficiency of the combustion process primarily by influencing temperature. Laboratory tests indicate minimum production of particulate, total hydrocarbon, and CO irrespective of type of wood waste or moisture content while temperature in the combustion zone remained above 1,100° F (593" C) (Prakash and Murray 1972). The same general relation has been reported by Darley et al. (1966) working with agricultural wastes. In piles, fuel elements in close proximity are heated by radiation from adjacent fuel elements. Fuels 'near the edge of the fire are heated less by both radiation and conduction, hence, are likely to burn cooler. Edge fuels are also subject to reduction of temperature by conduction from cool air entrained into the fire. Thus, the less the edge effect or the larger the pile, the higher the average temperature of the fire and the more complete the combustion. The smaller the pile, the greater the proportion of the pile near its periphery and the less complete the combustion.

Implications with respect to impact on air quality are:

1. Prepare fuels and firing plan to minimize the time in startup and die down stages. This favors pile burning since there is more opportunity to control fuel composition, arrangement, and moisture by covering, and to prolong the full fire stage by periodic "chunking in."

2. In the burning plan for area burning, make maximum use of the backing fire in lieu of a head fire. Darley et al. (see footnote 1) found greater emissions produced per unit of fuel by a head fire, possibly because its rapid movement cuts off an adequate supply of oxygen to the interior of the fire, and a large proportion of the broad flaming front is in the startup stage. A head fire, moving more rapidly, will burn off the light flashy fuels in a comparatively cool, inefficient flame, unsupported by the hotter fire of the slower burning, larger fuels. In a backing fire, there is more likelihood of overlap between startup and full fire stages, thus assuring better combustion of the distillation products of the startup phase.

3. In the broadcast burn, much of the area may have only a light cover of fuel that will produce a comparatively cool and inefficient fire. Fuel concentrations will burn hotter like piles. Because of the scattered nature of the fuel, the smoldering or die down stage will be reached earlier than with piled fuel.

4. The fast moving wildfire, burning in both green and dead fuels, is probably less efficient than any controlled burn. Though it burns large areas quickly, the flaming front is likely to be predominantly in the startup stage so that much pyrolyzed material escapes unburned. Its width and depth limit air supply to the interior of the flaming front, further limiting efficiency of combustion. Low concentration of fuels in weight per unit volume is likely, further reducing burning efficiency.

5. The prescribed underburning fire is also likely to be comparatively cool with inefficient combustion except when it reaches concentrations of dry fuel. A backing underburn would be more efficient than a head-fire underburn.

6. Maximum efficiency of combustion is gained with a continuing fire to which fuel is added at a rate that keeps it in the full fire stage and provides for combustion of the distillation products emitted by the added fuels in the startup stage. Efficiency may be further enhanced by forced draft and recirculation of emissions assuring adequate oxygen, complete combustion of emissions, and a continuing hot fire. Concentration of fuels and heat limits the die down stage. Forced draft burners have been shown to produce almost no visible emissions.

7. Fuels such as duff and rotted wood tend toward glowing combustion, hence by themselves will be smoke producers. If this kind of material is omitted from the burn, as in the yarded piles of slash and other clean piles, more efficient combustion is likely.

SMOKE CONVECTIVE COLUMN BEHAVIOR

The smoke column over a fire is similar to a chimney. To operate, it requires a source of hot gases at the base--the hotter the gases, the better it operates. But the convective "chimney" is affected by mechanical and thermal conditions in the air around it. The "chimney" operates as long as the energy of the column is greater than that of the outside wind forces acting upon it. The energy of the column is buoyant energy which translates into upward momentum. Buoyant energy depends on the difference in temperature between the gases within the column and the outside air surrounding it.

The temperature of the rising hot gases always decreases with height as a result of mixing with entrained outside air, radiational cooling, and expansion. The smaller the column diameter, the more rapid the effect of radiational cooling and particularly of mixing with the outside air. The large, very hot column sustains considerable momentum and mixes less with the ambient air. Countryman (1964) has observed intense convective columns acting as solid obstacles, the horizontal airflow splitting and flowing around the column. This holds true only as long as the upward momentum of gases in the column exceeds the horizontal momentum of the winds in the ambient air. Because the large, hot column is a more efficient "chimney," it will achieve maximum smoke rise. For this reason, producing the hottest, largest convective column possible for the given burning job by high temperature burning over a maximum area is desirable. Of course, other considerations, such as desired intensity of burn and danger of excessive horizontal indraft winds into the fire, must be weighed.

Column buoyancy also changes with the temperature of the ambient air through which it ascends. When column and ambient air temperatures become equal, buoyancy is lost. The rate at which the temperature of the outside air changes with height varies considerably with the weather situation. It may decrease, remain constant, or increase. When the temperature of the air increases with height, as within an inversion, the air temperature may equal that of the rising hot gases at a considerably lower elevation. For this reason, inversions often stop the rise of a convective column.

Convective smoke columns rise to greatest height through ambient air that cools rapidly with increasing height; i.e., through air that is least stable. Stability is an airmass characteristic and in moist airmasses is evidenced by type of clouds--vertical clouds and development of cumulus clouds in unstable air that supports vertical motion, and horizontally stratified clouds in air that suppresses vertical motion., Unstable airmasses are most common in spring months and stable airmasses in autumn (Schroeder and Buck 1970), though stability changes from day to day with changing weather patterns in every season.

Degree of stability in the surface layers is closely related to diurnal conditions. On sunny days, surface heating gradually warms a deepening layer through which convective mixing takes place. In mountainous terrain, this heating produces upslope winds that terminate in rising thermals of warmer air above the peaks and ridgetops. The depth heated by turbulent convection from the surface during the day is called the *mixing Zayer*. During the heat of the day, smoke column rise is aided by natural currents of rising heated air within the mixing layer. Lesser plumes without a defined column become diffused throughout the mixing layer. In mountainous areas, the mixing layer extends higher than over flat country (Cramer 1972). Strong convective columns may rise completely through the mixing layer and carry smoke to potentially warmer layers, from which it cannot descend unless the entire layer descends as in subsidence or mountain wave-type winds.

During clear nights, as a sequel of surface cooling, the mixing layer is replaced by a surface inversion layer. This nocturnal inversion in the valleys is further fed by cold air drainage off the slopes. Ridges and peaks may extend above this very stable layer into air that is only slightly more stable than during the day. For this reason, convective columns at night may be limited in rise from valley locations; on the other hand, ascent from fires above the inversion, though less than during the day, will still be substantial. Application of this information to prescribed burning can be summed:

1. Fires in all locations will push smoke to the highest elevation if burned so as to produce a strong convective column during the hottest part of the day.

2. Fires in mountain areas may be expected to produce strong convective columns at night from locations above the valley inversion.

3. Strong convective columns will often place most of the smoke produced during the mature fire stage completely above layers of air that come in contact with the earth's surface.

4. Smoke from fires with weak convective columns will be dispersed within the mixing layer during the day but at night will be dispersed vertically very little.

5. If the fire prescription limits intensity of fire, the convection column can be reinforced by providing maximum area aflame through such techniques as prewired circuits of incendiary devices for area ignition (Schimke et al. (1969).

SMOKE PLUME BEHAVIOR

Nonbuoyant smoke from a particular source but not in a well-defined convective column is called a *plume*. A plume lacks definite boundaries or shape and is subject to the motions of the ambient air in which it lies. It may come directly from a weak fire, from a fire on a windy day, or from the top of a convective column that has reached neutral buoyancy.

Once a smoke column has cooled to the plume stage, condensation of vapors into particulate is probably complete. As is described in more detail later, change in distribution of particle sizes is very slow after smaller particles have agglomerated to the 0.1- to 1.0-μ class (Robinson and Robbins 1971). Most of the particulate is too small to fall out so that the dominant processes are likely to be diffusion and removal related to precipitation processes.

Plume behavior is closely related to atmospheric motion controlled by wind and stability. In stable air and a light wind, even a small smoke source can form a long narrow band that remains identifiable for miles. Plumes issuing into still night air near the surface tend to follow the drainage with little dilution and to collect in low places. It is this characteristic of smoldering fires remaining after major burning operations that is most likely to be of concern in smoke-sensitive areas. Smoke from a large source will spread out horizontally in a sheet at the level at which it reaches neutral buoyancy. In unstable air, the normal horizontal gustiness and vertical thermals and turbulent motions will tend to disperse the plume through the unstable layer within an expanding cone-shaped volume. The surface unstable or mixing layer varies from quite shallow in the winter to 15,000 feet (4,572 m) deep over the interior in the summer, subject to airmass, cloudiness, and windspeed.

Smoke plumes above the mixing layer acquire a characteristic temperature-pressure relationship (potential temperature) that remains nearly constant. Behavior and trajectory of these plumes can be predicted from the potential temperature and wind structure of the airmass[3/] and the upper wind patterns--factors familiar to a fire-weather forecaster. Many diffusion, models have been developed to approximate dispersion of pollutant plumes in metropolitan areas within the mixing layer. They are useful for estimating effect on pollution concentration, patterns of changes in locations, numbers, heights, and amounts of emissions from usual metropolitan area sources but are less applicable in complex mountainous terrain with transient point sources, sparse observing stations, and dominating terrain influences.

IMPORTANCE OF FOREST EMISSIONS

The forest obviously is composed of a complex of higher plants, animals, fungi, and bacteria that, while living, carry on respiration involving uptake and release of various gases to the air. Wastes from the living organisms and dead materials decompose, also involving uptake and release of various gases. The most rapid conversion of forest materials, both living and dead, into atmospheric components is through fire.

Regulations of sources of forest smoke treat such smoke as a pollutant that must be either severely limited or entirely eliminated. This would imply that wood smoke contains toxic, irritating, or harmful chemicals that contribute significantly to the effects of air pollution on health, welfare, plants, animals, materials, and possibly weather. Although additional research is needed to identify the specific compounds produced by prescribed fire in the usual component fuels, the rather considerable evidence to date rates wood smoke components on a par with the normal products of such processes as forest respiration, photosynthesis, and decay that are going on continuously in the forest (Hall 1972). Natural forest emissions are more prevalent but at greater dilution. However, if smoke from forest fuels actually constitutes a serious complex of pollutants, then the threat of significant pollution episodes from the extremely dense smoke of forest wildfires becomes an even more important consideration.

FIRE EMISSIONS

Whereas emissions from the growing forest and from decaying forest residue are more or less continuous, emissions from fire are more spasmodic and in denser local concentration. Emissions from prescribed fire are normally limited to periods of moderately dry weather with light winds; i.e., to conditions under which burning can be accomplished and the fire kept under control. The practice has generally been to await such favorable conditions. Under air quality restrictions, the definition of "favorable conditions" has become further limited. Fortunately, it is within man's discretionary power to select the weather, time, place, manner, and fuel of prescribed burns so that the fire is controlled and the emissions are released when they will be the least nuisance.

3/ Owen P. Cramer. Implications of atmospheric potential temperature structure on the distribution of aerosols in western Oregon. Paper presented to Pacific Northwest International Section Meeting, Air Pollution Control Association, Salem, Oregon, Nov. 9, 6 p. 1967.

Man has little control over the conditions during which conflagration-scale wildfires occur. He knows that the weather will be extreme--very dry and windy. Control usually depends on the weather moderating. Destruction of property, forest, wildlife, and soil are the greatest concern--the smoke of a conflagration, though often dense, is only incidental. Yet, some of the historic air pollution episodes around the world have resulted from forest conflagrations (Plummer 1912, Murphy et al. 1970). Inconsequential as the smoke from a conflagration may be in comparison with damage, it is this renegade smoke that has real air quality significance and which, if we wait until a conflagration is burning before worrying about it, is impossible to cope with. Fortunately, conflagrations can be greatly reduced, though possibly not completely prevented, by fuel management (Martin and Brackebusch 7974). Fuels that would support a conflagration are removed by various means including prescribed fire. So, here is a trade off--a small amount of smoke, where burning is necessary, under conditions when the smoke can be managed, in trade for the extreme damage of the conflagration and incidentally its potential for producing a smoke pollution episode. From the standpoint of environmental trade off, and considering all the resources involved and the duration of the effects, all the advantages seem to be with conflagration prevention.

Unfortunately, emissions from forestry uses of fire have not always been released under conditions producing the least impact. Though the maintenance of good visibility for fire detection purposes has been a consideration of fire control agencies for decades, smoke management systems for minimizing impact on atmospheric transparency for other purposes have been proposed in only the last few years.[4/] [5/] (Cramer and Graham 1971). Despite these efforts and the potential for greater progress, memories of the presmoke-management days linger. And occasionally, all the variables, such as weather, of a prescribed burning operation do not work out as planned. Such uncertainty is not unique to prescribed burning--even the most sophisticated emission control devices malfunction occasionally. Although some parts of the country have weather, terrain, and forest conditions that favor satisfactory operation of smoke management systems, in other regions ideal conditions may be rare. Because of the great diversity of situations that control the impact of prescribed burning on atmospheric transparency, the type of smoke management plan and the kinds of restrictions imposed should be designed to fit the local problem.

Little research has been conducted directly on the effects of forest smoke; and because forest smoke is of such transitory nature and rarely the only impurity present, a precise evaluation of the impact of smoke from forest fuels cannot be made at this time. Statements can be made about its prevalence and about some of its more plentiful components and their properties.

4/ William R. Beaufait and Owen P. Cramer. Prescribed fire smoke dispersion principles. U.S. Department of Agriculture, Forest Service, Northern Region (in-Service distribution), Missoula, Montana, 12 p., illus., 1969.

5/ James A. Pharo. An interim smoke management guide for the South, Part I: Head and backfires. Unpublished manuscript on file at Southern Forest Fire Laboratory, Macon, Georgia, 1972.

Recently, Biswell[6] reported beneficial effects of forest smoke. Research currently underway indicates that a few seconds exposure to smoke kills the spores of some important forest pathogens including *Cronartium harknessii*. Smoke may also accelerate the rate of decay of forest residue. Finally, the carbon particles, like activated carbon in a gas mask, adsorb pollutant gases, thereby cleansing the a r.

The amount of smoke in the atmosphere is a function of the area of forest burned. In the Pacific Northwest, the area burned annually in forest wildfires decreased up to the 1940's under the policy of wildfire exclusion established about 1910. Th s policy required the abatement of hazardous logging slash, usually by burn ng. But such factors as better utilization. improved fire control, and more recently, limitations on amount and timing of' slash burning for air quality reasons have reduced the practice of broadcast burning over the past 20 years. In November 1968, the Oregon Forest Log (Oregon State Department of Forestry 1968), for example, reported a reduction in slash acreage burned annually on State and private lands in western Oregon from 149,000 acres (60,300 ha) in 1949 to 56,000 acres (22,663 ha) in 1968.

Persistence and travel of forest smoke in the air have long been recognized. The movements of vast smoke plumes from huge forest fires have been recounted in the literature by many authors (Munn and Bolin 1971, Morris 1934, Plummer 1912). The most recent accounts dealt with the great Canadian fires of 1950 and the resultant smoke clouds over the Eastern United States, British Isles, and even Gibraltar.

The importance of forest smoke components may be partially judged by amounts emitted in comparison with amounts emitted by other natural and manmade sources and the average residence time in the atmosphere. To begin with, various authorities on combustion of forest fuels give the following approximate emissions for each ton of fuel:

	Pounds per ton burned		
	U.S. Environmental Protection Agency, Office of Air Programs (1972)	Darley et al.[7]	Cooper[8]
Water Vapor		About 1,000	
CO_2		1,600-2,500	
CO	60	40-140	
Hydrocarbons	20	4-18	
Suspended particulates	17	11-17	17-58
Nitrogen oxides	2		

6/ Harold H. Biswell. Problems of prescribed burning and smoke in urban areas. International Symposium on Air Quality and Smoke from Urban and Forest Fires Proceedings, Fort Collins, Colo., Oct. 23-26, 1973 (in preparation for publication by National Academy of Sciences).

7/ See footnote 1.

8/ See footnote 2. The 58 lb is for wildfire.

No attempt will be made here to duplicate the discussion of the chemistry of wood smoke components presented by Hall (1972). The total amounts of forest emissions are compared with emissions from man's activities and natural sources in table 2.

Emission factors for burning of forest 'fuels are anything but precise because of the great variation in fuels, fuel arrangement, moisture, ventilation, and type of burning--flaming vs. glowing and head fire vs. backing fire. The opportunity for selecting the most favorable conditions for complete combustion, hence least emission, if fully utilized, should provide significantly lower emission factors for prescribed burning than for wildfire.

Carbon monoxide.--With the identification of five isotopic varieties of CO by an Argonne National Laboratory team (Stevens et al. 1972), the most important source of CO has recently been found to be oxidation of methane by OH in the worldwide amount of 60 x 10^8 tons (54.4 x 10^8 metric tons) per year (Weinstock and Niki 1972, Maugh 1972).

Man releases 2.7 x 10^8 tons (2.4 x 10^8 metric tons) of CO annually, mostly from incomplete combustion in gasoline engines. Though comprising only 4.5 percent as much as the natural breakdown of methane, the auto is important because its emissions are concentrated in the surface layers in heavily populated areas. Forest fires are credited with 11.3 x 10^6 tons (10.25 x 10^6 metric tons) per year of CO (Robinson and Robbins 1969) or about 6.3 percent as much as auto emissions, almost entirely in remote areas and largely exhausted to higher elevations. More than five times the amount of CO from forest fuels comes from atmospheric reactions of terpenes, almost entirely from natural sources (Robinson and 'Robbins 1969). Air residence time varies from as little as 10 days in summer over land areas (Weinstock and Niki 1972) to an average of 0.1 year. Close to the surface in the presence of soil micro-organisms, CO residence time, under controlled conditions, may be reduced to hours.

Since the CO component of the atmosphere is holding constant (Weinstock and Niki 1972) and since burning of forest fuels contributes only one six-hundredth of the CO from natural sources, the contribution from forest burning does not appear to be of great importance except conceivably in isolated situations. But in an experimental 18-acre (7.3-ha) slash burn conducted by University of Washington, scientists found that, in both ground. smoke and the smoke plume aloft, CO concentrations decreased rapidly to ambient levels (Fritschen et al. 1970). Vines et al. (1971) did find a 5- to 20-fold increase of CO over clean air in smoke plumes from prescribed burns in Australia, far less than the CO concentration in a large city.

Hydrocarbons.--The most prevalent hydrocarbon in the atmosphere is methane, which is nonreactive photochemically and which originates primarily from decomposition of organic matter under swampy conditions at a world rate of 310 x 10^6 tons (281 x 10 metric tons) per year (Robinson and Robbins 1968). Tree foliage is the greatest natural source of reactive hydrocarbon, emitting terpene-class organics at a rate of 175 x 10^6 tons (159 x 10^6 metric tons) per year, approximately 6½ times the 27 x 10^6 tons (24.5 x 10^6 metric tons) per year of reactive olefins from man's activities (Rasmussen 1972). The 1.2 x 10^6 tons (1.1 x 10^6 metric tons) per year of reactive hydrocarbons from forest burning (Robinson and Robbins 1968) is comparatively minute compared with the constant natural emission of similar compounds. Only under very unusual circumstances would these emissions become a smog problem.

Table 2.--*Sources and amounts of some atmospheric components*

Chemical	Source	Annual amount worldwide	Emission factors	Characteristics
CO[a]	Autos	193 x 10^6 tons		
	Forest fires	11.3 x 10^6 tons		
	Terpene reactions	60 x 10^6 tons		
	Oceans	150 x 10^6 tons		
	Oxidation of CH_4	6 x 10^9 tons	(Forest fuels) (40-140 lb/ton) Ponderosa pine slash 195 ± 18 lb/ton	
Hydrocarbons[b]			4 - 18 lb/ton Green brush: 27.4 ± 8.8 lb/ton 11 ± 2 lb/ton ponderosa pine slash	
Methane	Bacterial decomposition, swamps, paddies, etc.	1.6 x 10^9 tons		Nonreactive
Terpenes	Tree foliage	1.75 x 10^8 tons		Reactive
Olefins	Man's activities	2.7 x 10^7 tons		Reactive
Reactive	Forest fires	0.25 x 10^6 tons		15% to 40% methane and ethylene
NO/NO_2[c]			NO_x 2 lb/ton from forest type fuels	Natural sources of NO/NO_2 exceed man's 15 to 1 NO/NO_2 participate in photochemical reactions involving SO_2 and reactive hydrocarbons (olefins from combustion sources and terpenes from the biosphere)
NO	Reduction of N compounds anaerobically by bacteria	501 x 10^6 tons		
NO_2	Forest fires	0.8 x 10^6 tons		
	Fossil fuel combustion	51.3 x 10^6 tons		
	Other combustion	0.8 x 10^6 tons		

See footnotes at end of table, p. 23.

Table 2.--*Sources and amounts of some atmospheric components--continued*

Chemical	Source	Annual amount worldwide	Emission factors	Characteristics
NH_3[c]	Biological action mostly in soil	1,160 x 10^6 tons		
	Combustion	4.2 x 10^6 tons		
Particulates[d]	Forest fires (U.S.) Worldwide	(2.1 x 10^6 tons) 3.3 x 10^6 tons	17 lb/ton fuel	Tar 55%, soot 25%, ash 20%
	Prescribed burn (U.S.): South West	(8.75 x 10^4 tons) (21.0 x 10^4 tons)	17 lb/ton 14 lb/ton	
	Woody materials		11 - 17 lb/ton	Particulate from head fires 3X greater, 3-10X more particulate when smoldering than flaming in litter and duff
	Ponderosa pine slash		12 ± 2 lb/ton	
	From gases: manmade (SO_2, NO_x, HC); natural (H_2S, NO_x, NH_3, HC)	296 x 10^6 905 x 10^6		30% in zone 30"-60" N. lat.
	Grass		16 lb/ton	
	Aerosol from terpenes, hydrocarbons, etc. (natural)	220 x 10^6 tons		
	Soil dust	200 x 10^6		
	Sea salt	1,000 x 10^6		

a/ McConnell et al. (1971); Weinstock and Niki (1972); Swinnerton et al. (1970); Darley et al. (see text footnote 1); Sandberg et al. (in press).

b/ Darley et al. (see text footnote 1); Darley et al. (1966); Rasmussen (1972); Sandberg et al. (in press).

c/ Robinson and Robbins (1970); U.S. Environmental Protection Agency, Office of Air Programs (1972).

d/ Vines et al. (1971); Darley et al. (see text footnote 1); Sandberg et al. (in press); Robinson and Robbins (1971).

Suspended particulates.--The visible quality of smoke is due to particulates in the size range 0.4 to 0.8 μ (micron). Because it can be seen, this part of forest fuel emissions receives the most attention. There are three main factors. (1) It obstructs visibility. (2) Visible emissions, regardless of composition, are associated by the public with all the bad qualities of air pollution,. (3) Suspended particulates have been designated as an emission component that must be controlled primarily because of its association with SO_2 in urban atmospheres. Incidentally, SO_2 is negligible in smoke from forest fuels (Hall 1972).

Though no increase in photochemical products was reported during periods of smoke from rice straw burning in the Sacramento valley, Evans et al. (1973) found definite increases in ozone with time in the top of smoke plumes from prescribed burning of eucalyptus litter in Australia.

Little work has been done directly on smoke particulate from forest fuels. Vines et a?. (1971), by aircraft sampling of smoke from large-scale prescribed burns in eucalyptus forests, found the typical composition to be 55 percent globular particles assumed to be tars, 25 percent soot, and 20 percent ash. They found that their particle sizes were mostly less than 1 μ with the majority about 0.1 μ in diameter with a concentration of 10^5-10^6 particles per cm^3. This size agrees with the findings of others.

Particulate effects vary with size (McKee and Church 1969):

less than 0.1 μ, cloud nucleation and possible weather modification;
0.4-0.8 μ, maximum light scattering and reduction of visibility;
1.0-5.0 μ, maximum deposit in lung.

With respect to weather effects, Hobbs and Locatelli (1969) found the number of ice nuclei nearly quadrupled in forest fire smoke in comparison with ambient air in the Washington Cascades. This is a very small increase compared with the increase in total particles, indicating that only a small proportion of the particles from that particular forest fire were ice nuclei. But Ruskin (1971) reported that simulated forest fire smoke produced no increase in cloud condensation nuclei, and Hobbs et al. (1970) reported sawmill waste burners were prolific sources of cloud condensation nuclei. Schaefer (1969) noted distinct overseeding effects downwind from such particulate-producing phenomena as industrial and metropolitan areas, African bush and forest fires, blowing soil, and Hawaiian sugarcane burning. The effects reported were extensive areas of very fine water droplet or ice crystal clouds too small to fall out. Apparently, more investigation is needed of cloud-nucleating properties of forest fuel smokes.

Possibly smoke from forest fuels does not have uniform properties of nucleation because it is composed of many different chemicals. And these vary between fuels, completeness of combustion, and presence and amounts of various ash materials that influence the choice between flaming and glowing combustion. Thus, the suspended particulate of forest smoke has many possible components with many possible properties.

The heterogeneity of particulate and its apparent teaming up with other chemicals have led to possible oversimplification. Hemeon (1973) points out that, although standards based on health criteria have been set for suspended particulate, its composition has not been defined. He contends that the regulations are not actually based on the effects of particulate, but rather on the synergistic effects of the minute particles in combination with SO_2. Hemeon holds that it is not logical that unspecified particulate be regulated as a health hazard since there has been no evidence of adverse effect of particulate on people since the virtual abolition of coal smoke. Forest smoke is almost devoid of sulfur, so there is a definite question as to whether the criteria set for regulation of particulate in the presence of SO_2 really are pertinent to wood smoke. Though most forest smoke is unlikely to mix with an SO_2 source, if it does it might be expected to act as do other particulate sources. Unfortunately, there is no experimental evidence upon which to formulate criteria for forest smoke.

Secondary standards relate to protection of public welfare, and this includes visibility. Smoke particulate from incomplete combustion of forest fuels is important especially as a reducer of visibility. This is obviously important in such situations as surface smoke plumes crossing vehicular thoroughfares. Visibility reduction is also undesirable where it unreasonably interferes with enjoyment of the distant scenery.

Nitrogen *oxides*.--Nitric oxide (NO) is primarily important because of its participation in photochemical smog processes which in turn produce damaging chemicals such as O_3, NO_2, and PAN (peroxyacetylnitrate). NO is not a combustion product but forms in amounts that increase with temperature wherever air is heated higher than 1,540° C (2,804' F) (Hall 1972, U.S. National Air Pollution Control Administration 1970), a temperature that may be exceeded in extremely hot fires (Countryman 1969). Nitrogen compounds in living plants and soil are generally broken down to gaseous nitrogen by fire. Darley (personal communication) has found NO release up to 70-80 p/m during the few seconds of peak temperature in test fires. On a global basis, natural production of NO, apparently mostly by soil organisms, exceeds man's production by 15 to 1, and forest fires are an insignificant source (Robinson and Robbins 1968). The Environmental Protection Agency recently indicated that NO_2 (which forms readily in sunlight from NO and oxygen) is not the problem it was once thought to be (Air and Water News 6/11/73). The change resulted from findings that previous methods for measuring the concentration (Federal Reference Method) indicated amounts 200 percent of actual amounts.

FROM THE LIVING FOREST

If one considers the atmosphere pure except for emissions from man's activities plus possibly duststorms, volcanoes, and forest fires, it is enlightening that photochemically reactive hydrocarbons released by living tree foliage exceed the reactive hydrocarbons released by man on a ratio of 6 to 1 (Rasmussen 1972). These compounds include many gaseous olefins that react in the atmosphere with NO_2 to form the minute particulate that gives rise to the so-called blue haze, reactions reported by Went (1960). Though the atmospheric photochemical activity in nature greatly exceeds that from man's emissions, it is generally well dispersed and offers no problem. Lovelock (1971) did report, however, that tropical forests appeared in satellite pictures to be covered by either a blue photochemical haze, or by smoke from slash-and-burn agricultural practice, to a greater extent than industrial regions of North America or Europe.

FROM THE DECAYING FOREST

Hall (1972) reviewed the findings on release of chemicals that might be otherwise classed as pollutants into the air by dying vegetation and deciduous trees at the time of leaf abscission in the fall. These include the reactive hydrocarbons--ethylene, isoprene, α-pinene (Rasmussen 1972). Accumulations of vegetative material under swampy conditions produce marsh gas or methane, the most common hydrocarbon that is always present in the atmosphere. The breakdown of methane in turn provides the greatest source of CO (Weinstock and Niki 1972). None of these sources appear to be subject to appreciable manipulation by residue management.

AIR POLLUTION REMOVAL MECHANISMS

Many substances continuously flow into the atmosphere from natural sources including living as well as decaying organic matter, volcanic activity, dust-storms, and lightning fires. To these are added man's sources. Yet the atmosphere maintains a balance with only CO_2 apparently increasing, and some fear that particulate may be headed in the same direction in portions of the North Temperate Zone. Continuing balance requires that removal mechanisms operate at the same annual rate as the sources. Where removal mechanisms operate more slowly than sources or are at locations distant from the source, considerable interim accumulation may occur, and vast areas may be covered as the burdened airmass moves from source to sink.

The processes and rates of removal of the various components in forest fuel emissions can influence management of the activities that produce them. Precipitation processes remove considerable material, mostly particulate but also gaseous compounds; and the occurrence of precipitation can be predicted with some skill. The amount of moisture and stability of the airmass, the probable trajectory, and atmospheric circulation pattern give indication of likelihood of precipitation. To protect air quality, long lasting emissions might be withheld from dry airmasses that show little prospect of supporting precipitation.

Atmospheric reactions may alter emitted chemicals either to produce chemicals that may be less desirable or to form other chemicals that are sufficiently innocuous to be considered a sink. Many kinds of reactions may occur, some dependent on sunlight and some not. Gases or vapors may react to form particulate which may act as precipitation nuclei or be washed out.

At the surface, other removal mechanisms operate. Plants take up and metabolize some gases such as CO_2, O_3, NO_2, and SO_2 (Hill 1971). Soluble chemicals are likely to be removed during long passages over bodies of water. But surface mechanisms may operate slowly unless there is vertical mixing. All these mechanisms play a part in keeping emissions from forest fuels in balance. Residence times, background concentrations in comparison with national ambient air standards, and removal mechanisms are summarized in table 3.

CARBON MONOXIDE

Recent discoveries have shown that the breakdown of methane in the air produced CO at a rate 20 times that of all combustion sources (Weinstock and Niki 1972) and that soil micro-organisms in the United States alone have a capacity to remove 3 times man's worldwide CO production. Of course, this is subject to the limitations of a process acting only at the surface; but CO may also be oxidized in large quantities in the atmosphere by the hydroxyl radical (OH) (Robinson and Robbins 1969). Since CO can be removed by soil fungi at an average rate of 8.44 mg/m^2 (7.53×10^{-2} lb/acre) per hour (Inman

Table 3.-- ***Background, residence times, and removal mechanisms of some atmospheric components***

Chemical	Total annual emission (global)	Average background	National standards Primary	National standards Secondary	Residence time	Removal mechanism
CO[a]	6,221 x 10^6 tons natural sources 274 x 10^6 tons man's sources	0.1-0.3 p/m	9 p/m 8 h max* 35 p/m 1 h max*	(Same as primary)	10 days in summer 0.1 yr	Oxidation $CO+OH \rightarrow CO_2+H$ Uptake by soil microbiota
Hydrocarbon&			0.24 p/m 3 h max*	(Same as primary)		
Methane	1,600 x 10^6 tons natural sources	1.5 p/m			1.5 yr	Oxidation to CO
Terpenes	175 x 10^8 tons natural sources	< 1 p/b			Few hours	Photochemical reactions with NO/NO_2, O_3 forming other gaseous compounds and particulates
Olefins	27 x 10^6 tons man's sources				Few hours	
NO/NO_2[c]			NO/NO_2 0.05 p/m	(Same as primary)		
NO	501 x 10^6 tons natural sources	2 p/b land 65°N - 65°S All other areas 0.2 p/b			4 days	Oxidation by O_3 Photochemical reactions
NO_2	52.9 x 10^6 tons man's sources	4 p/b land 65 N°- 65°X All other areas 0.5 p/b			3 days	Microbial degradation combines with H20 to form nitric acid which reacts with ammonia to form ammonium nitrate, a hygroscopic particle
NH_3[c]	1,164 x 10^6 tons natural sources	6 p/b			1 week or less	Gaseous deposition Aerosol deposition (reaction with SO_2 to form $(NH_4)SO_4$) Oxidation to nitrate
Particulates[d]	2,300 x 10^6 tons natural sources 296 x 10^6 tons man's sources	Organic 1-5 mg/m^3 Ammonia aerosols <1 mg/m^3 Nitrate aerosols <1 mg/m^3 Sulfate aerosols 2-5 mg/m^3 Insoluble 10 mg/m^3 in middle latitudes	75 mg/m^3 Annual geometric mean 260 mg/m^3 24 h max*	60 mg/m^3 Annual geometric mean 150 mg/m^3 24 h max*	Varies by size and composition <12 h	<0.01 μ radius--agglomerate rapidly <0.1 μ radius --agglomerate more slowly 0.1-1 μ radius--rainout, more persistent >1 μ radius--washout and fallout

*Not to be exceeded more than once per year.

a/ Robinson and Robbins (1968), Weinstock and Niki (1972), Inman et al. (1971), Anonymous (1972).

b/ Robinson and Robbins (1969), Weinstock and Niki (1972), Rasmussen (1972).

c/ Robinson and Robbins (1970).

d/ Robinson and Robbins (1971).

et al. 1971), or by the average soil in temperate zone climates at a rate of 210 tons/mi^2 (736 kg/ha) per year, and since this rate varies by temperature, soil pH, organic content, and species of fungi, there may be possibilities for enhancing CO removal in regions of concentration by providing open areas where soil micro-organisms, possibly such as those in the forest floor, may flourish. Of 17 soils tested, soil from northern California coast redwoods consumed CO at the most rapid rate. But high concentrations for prolonged periods--over 50 p/m for 25-40 days--reduced the rate of CO removal.

Though CO may still be important in large metropolitan areas, scientists of the Institute of Environmental Medicine at the New York University Medical Center believe CO has decreased in urban atmospheres since 1922 due to changes in fuel for space heating and power production and may now be lower than at any time since man first learned to use fire (Eisenbud and Ehrlich 1972). Because of its comparatively low concentrations in forest smoke, short air life, and adequate removal mechanisms, CO from burning of forest fuels does not appear to be an important air contaminant on a global long-term basis. However, it could conceivably add temporarily to local CO concentrations if the trajectory of the smoke is short and near the surface.

HYDROCARBONS

Many different chemicals including gases, liquids, and solids of many densities and representing a broad spectrum of reactivity make up the hydrocarbons found in emissions from combustion of forest fuel (Hall 1972). These dozens of compounds can be grouped to some extent by chemical reactivity in the atmosphere; this will help in describing their removal mechanisms.

Some gaseous hydrocarbons, such as the olefins, are chemically reactive and may produce additional fine particulate as blue haze. If NO or NO_2 are also present in sufficient concentration, the olefins may enter into some of the photochemical smog-type reactions, forming particulate and other gases. Some nonreactive hydrocarbons such as methane may gradually be oxidized to form CO and OH. Components of the soil may also take up some of the reactive hydrocarbons such as ethelyne (Abeles et al. 1971). At this time, not much is known about the specific removal mechanisms for most hydrocarbons likely to be in forest fuel smoke. Since there is some indication that plants and soil may take up some hydrocarbon, possibly in some localities, maintaining the soil and its plant cover in a condition most favorable to hydrocarbon removal may be important in the residue management process. This would most likely be where hydrocarbons from sources other than the forest are a problem.

SUSPENDED PARTICULATES

Suspended particulates, even more than hydrocarbons, are an extremely heterogeneous group that includes a multitude of substances with different properties. Vines et al. (1971) divided the particulate related to smoke from forest fuels into broad divisions of tarry droplets, soot, and ash. We must also be concerned with the minute particulate which must be assumed to result from subsequent photochemical reactions involving the gaseous terpenes and olefins.

Though direct research on removal of forest smoke particulate has not been done, we can draw some conclusions from related research. First, we should note that particulate *is* removed--global accumulation has not been observed although increased turbidity in the heavily populated and industrialized North Temperate Zone has already been reported. Precipitation is generally conceded to be the great cleanser of the atmosphere (Robinson and Robbins 1971), but most of the research has been on removal of radioactive particles. Fuquay (1970) observed that particles less than 1 μ are not likely to be removed by collision with raindrops; but probability of such removal is increased by electrical charge; and many precipitating cloud systems are charged, especially those with ice phase precipitation. Snowflakes (present in higher or colder clouds) are more likely to carry an electrical charge and have been observed to collect the minute Aitken particles less than 0.02 μ. Incloud scavenging is more complex than below-cloud washout and is believed to be more effective (Engelmann 1970) for both submicron particles and gases.

Robinson and Robbins (1971) summarize the knowledge of removal characteristics of various size classes of particles. The smallest, less than 0.01-μ radius, agglomerate readily into larger particles about 0.1-μ radius. This process is completed in a few hours in dry air. Within a waterdrop cloud, agglomeration proceeds more rapidly with these minute particles picked up by cloud droplets within minutes. Similar processes proceed more slowly for particles in the 0.01- to 0.1-μ radius class, which also .decrease in number in favor of larger particles about 0.1-μ radius.

Particles 0.1 μ to 1.0 μ in diameter are most important. This not only is the predominant size class of smoke particles but also includes the important common sulfate and photochemical aerosols. This size particle is least susceptible to the usual removal mechanisms. Agglomeration and below-cloud scavenging by precipitation are quite inefficient. Inclusion in cloud and rain droplets is the most likely removal process. Successive cycles of drop formation and evaporation lead to larger size particles that become increasingly susceptible to removal in precipitation. By comparison, particles larger than 1 μ in radius were readily collected by raindrops.

Of the many kinds of particulate found in the atmosphere, the greatest proportion are hygroscopic, hence, excel as droplet nuclei. Ammonium sulfate and other particulates produced by chemical combination of gases (H_2S, SO_2, NH_3, NO, NO_2, hydrocarbons other than methane) *within* the atmosphere account for about one-half the aerosol matter on a global basis (Junge 1972).

Particles acting as either condensation nuclei or ice nuclei are most likely to be removed in a precipitating cloud system as moisture condenses on them; that is, by rainout. Hobbs and Radke (1969) found cloud condensation nuclei increased by a factor of 2.5 in smoke from slash burning.

Though we can be reasonably certain that much smoke particulate would be removed by the condensation, coalescence, and precipitation processes that go on within active clouds, little research has been done on natural processes of removal of smoke from the atmosphere. Mason (1957) reported that 95 percent of the precipitation nuclei were combustion products. Since precipitation processes seem to be the primary mechanism for removing smoke from the atmosphere, smoke residence time can best be minimized by burning when smoke will enter a precipitating cloud system. A compromise would be into a moist airmass with an expectancy of a trajectory toward a moisture gathering source region and precipitation favoring circulation patterns.

Nitrogen oxides.--NO and NO_2 are photochemically active and tend to change from one to the other in the sunlight. In the presence of manmade or natural reactive hydrocarbons, a long series of reactions occur to produce ozone, PAN, and other compounds damaging to decorative and agricultural plants, materials, and even forest trees. If SO_2 is present, particulate ammonium sulfate is formed. The average air residence time of NO and NO_2 is short because of reaction and change into various aerosols. Particularly in forest areas away from urban pollution, the nitrogen oxides, produced in very small amounts by forestry uses of fire, are not a problem.

SMOKE MANAGEMENT POSSIBILITIES

Permitting open burning of unwanted solid waste, thereby placing great tonnages of combustion products in the air, may be quite unacceptable to a lot of people as attested to by laws either prohibiting or severely regulating open burning. But permitting these solid wastes to accumulate, thereby inhibiting the culture of needed wood and, at the same time, increasing the risk of a severely damaging fire, is also quite unacceptable. Accomplishing the waste removal job by other methods may also have environmental and economic consequences that are unacceptable, again, to a Jot of people. So we must examine the possibility that on balance the carefully regulated use of fire may be less unacceptable than other alternatives, in some situations. But if fire becomes a plausible alternative, it is likely to be only on the basis that the undesirable effects of smoke are acceptably minimized. This may be done by attention to fuel preparation, as discussed above, and by taking full advantage of the flexibility permitted in scheduling to achieve the optimum diffusion, diversion, separation, obscuration, and washout of each smoke from each particular source; i.e., by *smoke* ***management.***

Smoke management approaches the concept of maintaining air quality by avoiding unacceptable combinations of concentration, duration, and place. As stated in the 1971 Annual Report of the Council on Environmental Quality (p. 213):

> Measuring pollutants by tons emitted also ignores their geographical distribution. We are generally concerned with the concentration of pollutants in a particular place, but measuring total weight of of emissions tells us nothing about their concentrations.

In particular, smoke management is aimed at excluding smoke in excessive concentrations from areas where 'it would be a nuisance or would add to an existing air quality problem. The tonnages of smoke components processed in nature's atmospheric cleansing systems without making or contributing to a local pollution problem, in view of the findings reported above, are deemed to be primarily of academic interest and without important environmental impacts. But with smoke persistence and the rigid requirements of ambient air standards on suspended particulate, real practical problems face smoke managers.

A smoke management system, to be successful, must satisfy certain conditions:

1. It must be possible to define certain airspaces and surface areas from which prescribed burn smoke in specified concentration must be excluded. Such areas would include metropolitan centers with their own chronic air quality problems. This presumes the availability of other airspace for smoke transport and dispersion.

2. Accurate predictions must be available of the factors governing smoke column rise, depth of the mixing layer, direction and speed of winds at plume height, and rate of dispersion of smoke at the fire and along the smoke trajectory.

3. Procedures are necessary for interpreting weather forecasts in terms of amounts of fuel that may be burned in various locations.

4. Burning operations must be under administrative control.

5. The burner must have physical control over burning procedure to produce the necessary convective column or fire intensity and also to stop the fire if dispersion conditions become unfavorable.

With these requirements satisfied, smoke impact on air quality can be managed by deferring burning when conditions are not favorable and by selective burning when conditions are favorable (Dell et al. 1970). Determination of the burning to be allowed may be based on such processes as: (1) diffusion, (2) diversion, (3) separation, and (4) obscuration and washout.

DIFFUSION

By molecular motion, turbulence, and small eddies, smoke plumes tend to mix with and disperse into the air around them. In many forest situations, the area needing treatment by fire is in the same elevation range as sensitive areas nearby. Here, in the absence of a strong convection column to lift the smoke to a higher level or of wind to dilute and move it, diffusion may be the predominant means of smoke dispersion. Under such conditions, burning may have to be delayed until the conditions of turbulent mixing and depth of the mixing layer provide for the necessary dilution of the expected volume of smoke within the available downwind distance. Allowance for diffusion of smoke plumes in the layer of air in contact with the surface and a plume rise model form the basis for an existing smoke management system (see footnote 5) for Georgia. Diffusion with distance and depth of mixing layer is the principle behind one option of the systems used by forestry agencies in Oregon and Washington, and by the Forest Service in California. The basic parameters are wind, stability, and distance. Predictions of the weather conditions and the existing concentration of air impurities are also necessary.

Air quality implementation plans for metropolitan areas and evaluation of effects of new emission sources are usually based on diffusion models that simulate the patterns of concentrations resulting from known emission sources under various wind and stability conditions.

DIVERSION

In many forest situations it may be possible to await a wind direction that will simply blow the smoke away from sensitive areas. This option makes use of the weather forecaster's skill to predict wind. It is particularly applicable to burns producing at least a partially elevated plume that will not cause a problem at the surface in the vicinity of the fire. This principle is used in the West where most forest areas are remote from sensitive areas. It is not appropriate for low energy fires in populated areas unless used in combination with diffusion requirements. Diffusion becomes a consideration also if there are additional sensitive areas downwind.

SEPARATION

With stable air, as at night and during the cooler part of the year, air strata are thermally prevented from mixing vertically. Because such a condition tends to hold metropolitan area emissions in the surface layers, it also prevents any emission or smoke plume in a higher layer from descending into lower layers. Mountainous terrain often extends up into air strata that are thermally separated from valley air that may cover smoke-sensitive areas. Terrain elevation, plus the additional elevation gained by the convective column, provides for complete avoidance of contamination of low-elevation sensitive areas from forestry smokes originating at higher elevations.

OBSCURATION AND WASHOUT

The discussion above of removal mechanisms would seem to indicate that a most effective device for satisfying air quality requirements of prescribed burning is venting the convective column directly into a precipitating cloud system. This immediately limits the type of burn to heavy accumulations of fuel, usually in prepared piles. It also requires accurate detailed forecasts of plume rise and cloud levels to identify conditions under which a plume will enter the precipitating cloud layers. The theory is that the hygroscopic smoke particles will act as condensation nuclei around which droplets will form, then coalesce and precipitate. The theory needs further checking, but processes of precipitation do require particle nuclei for sublimation or condensation. Much of the burning in Pacific coast forests is of large piles or of smaller covered piles that can be ignited after the autumn rains. Release of smoke into the clouds of a saturated airmass from which precipitation is already falling promises quick removal of soluble gases and particulate in nature's air scrubber--the same principle applied in scrubbers for removing particulate and gases from stack emission.

MINIMIZING EMISSIONS

An obviously desirable alternative is burning with zero emissions. Converting wood into water vapor and CO_2 is theoretically possible, but conditions are usually such that many partial combustion products are released in the form of particulate, CO, and gaseous hydrocarbons and relatives. Insofar as the objectives of prescribed burning will permit, the fuels should be as dry and burned as hot as possible to achieve the most complete combustion. The damper the fuel, the lower the combustion temperature, the less efficient the combustion process, and the denser the smoke. In addition, flaming combustion produces a small fraction of the smoke components given off in glowing combustion.

Combustion can be aided by improving the air supply. This may be accomplished to some extent by arranging fuel for air space and minimizing soil in piles. A blower helps, and a strong forced-draft 'in a confined burning pit or bin simulates the effiency of an incinerator. Effectiveness of an open pit incinerator[9] and of a portable open bin incinerator[10] for burning even large damp material almost without visible emission has been demonstrated.

SMOKE MANAGEMENT SYSTEMS

State and local agencies charged with achieving ambient air standards have several approaches for regulating the various kinds of prescribed burning for forestry purposes and known in air pollution parlance as *nonpoint* ***sources open*** *burning*. The easiest control is to ignore any subsequent problems and prohibit all such burning. This is environmentally irresponsible unless satisfactory alternative treatments have been found adequate. One approach has been to prohibit burning on a large proportion of days on the basis of an index such as the air pressure at 16,000 to 19,000 feet (4,877 to 5,791 m). Though this is a meteorological measurement, it has little relation to the wind and stability conditions that must be considered to determine whether smoke dispersal from a particular forestry prescription burn in mountain areas will be away from smoke-sensitive areas.

A more direct approach is the use of a smoke management system based directly on the weather conditions that will affect smoke dispersal, existing air quality, amounts to be burned, kind of fire, and relative locations of burn and smoke-sensitive areas. According to J. Phil Campbell, Undersecretary of Agriculture (1971), "Real possibilities exist in smoke management systems which limit smoke concentrations and utilize favorable atmospheric conditions."[11] Some approaches for such a system are:

1. A system for the South based on (a) fuel loading, (b) rate of spread, (c) visibility, and (d) atmospheric stability (see footnote 5). This system is designed for mostly flat country and comparatively light burning without strong convective columns.

2. For San Francisco Bay area where a strong inversion is nearly always present, a system requires (a) at least a 2,500-foot (762-m) mixing layer, (b) wind greater than 10 mi/h (4.47 m/sec), and (c) wind direction that will minimize any smoke nuisance (Thuillier and Sandberg 1971).

9/ Michael B. Lambert. Efficiency and economy of an air curtain destructor used for slash disposal in the Northwest. USDA Forest Service Equipment Development Center, San Dimas, California. Paper Presented to American Society of Agricultural Engineers, Chicago, Illinois, December 11-15, 1972.

10/ Raymond L. Weholt. Combustion of wood wastes. The Camran Corporation, Seattle, Washington. Paper presented to Pacific Northwest International Section, Air Pollution Control Association, Eugene, Oregon, Nov. 17, 1972.

11/ J. Phil Campbell. Environmental improvement in the seventies. Paper presented to Environmental Seminar, U.S. Department of Agriculture, Washington, D.C., Jan. 5, 1971.

3. Bates et al.[12] have proposed use of stepwise discriminant analysis of weather variables related to visibility to estimate the acreage of grass straw that may be burned in the Willamette valley without reducing visibility below designated minimums.

4. Forestry agencies in Oregon and Washington use a smoke management system based on the principles described above of diffusion, diversion, separation, and obscuration and washout (Cramer and Graham 1971). This system has been used for several years and has greatly reduced complaints about slash smoke.

5. The Southern States of Alabama, Florida, Louisiana, North Carolina, South Carolina, Texas, and Virginia have worked closely with air pollution control agencies to develop specific guidelines under which prescribed burning can be done.[13] Details vary between States; but in general, burning is prohibited during air stagnation, Five States require a wind that will blow smoke away from sensitive areas, and visibility criteria must be met in five States.

Smoke management is not a simple process and thus far has not lent itself to complete automation, though progress toward this end is being made in the Pacific Northwest Region. While simple air transport and diffusion models yield accurate results, the problems imposed by local wind systems, topography, and a changing stability profile have not been solved (Singer and Freudenthal 1972).

AIR QUALITY MANAGEMENT CATEGORIES

From the standpoint of managers of an environment made up of all the natural resources, management of air quality is one important consideration but not necessarily the controlling consideration. In the case in point, forest residue also requires management, sometimes with techniques that may affect air quality. But most air quality regulations are concerned solely with air and are directed at sources and situations common to air stagnation basins and metropolitan areas where most air quality problems occur. Problems in these areas are often of such a nature that little flexibility is possible. And it is extremely important that forestry uses of fire not contribute to metropolitan area air quality problems. But, because of the nature of forestry burning operations and their mostly remote locations, more alternatives are physically open to the forest resource manager than if he were operating within a metropolitan area. The resource manager needs to know how his burning operations fit into the air quality picture. Though not necessarily taken into account by existing implementation plans for achieving ambient air standards, the considerations discussed below are important to determination of the real impact of forestry burning on air quality.

12/ E.M. Bates, D.O. Chilcote, and N.A. Hartmann. Agricultural field burning versus atmospheric visibility in the Willamette valley of Oregon. Paper presented at the 4th National Conference on Weather Forecasting and Analysis, American Meteorological Society, Portland, Oregon, May 1-4, 1972.

13/ Ernst V. Brender and Hugh E. Mobley. Rules and regulations about prescribed burning and air quality. Southern Forest Fire Laboratory, Macon, Georgia, 6 p., 1973.

SOURCE

Forest fuels are burned in many configurations from the low energy backing underburn, through piles of all sizes and distribution patterns, to the large broadcast burn in heavy fuels. Each type of burn has its own typical smoke production pattern--some with little convection energy placing the smoke plume in low layers and others producing strong convective columns. Large size and rapid rate of energy release may seem to indicate merely greater emissions, but they also indicate a stronger convection column and higher elevation release--distinct advantages for getting smoke above the mixing layer, or "pollutosphere" as Professor Fred Decker at Oregon State University, Corvallis, terms it. Most forestry smoke sources have some flexibility in burning pattern that may be used to accommodate differences in weather. They all are flexible in timing, hence can be scheduled to avoid periods of potential air pollution alerts. The largest, most important, as well as most uncertain source of serious pollution from forests is wildfire. Fortunately, the threat of devastating and polluting wildfire is lessened by abatement of serious fuel accumulations with prescribed burns scheduled under smoke management.

LOCATION

Most air quality regulations are aimed at sources within the areas where the pollution problems generally occur. Though some forestry burns may be within pollution problem areas, in many parts of the country there are both substantial horizontal and vertical separation of forestry burning from smoke-sensitive areas. With proper use of weather factors influencing convection and direction of smoke plume movement, this separation of forestry smokes from metropolitan air pollution problems can be increased. This is not to ignore burns that must follow the most rigid limitations because of proximity to pollution problem areas.

Vertical and horizontal differences in location and separation by weather regime may be ignored in statistics that lump all emissions from a so-called airshed. The implication is that the tonnages listed all affect the air quality of the problem areas in the bottom of the airshed. In the Willamette valley in Oregon, most forestry burning is not in the valley but in the bordering Coast and Cascade Ranges where it is separated by elevation differences of 1,000 to 3,000 feet (300 to 900 m) as well as by distances of up to 50 miles (80 km). Cramer and Westwood (1970) showed that, because of the prevailing weather, slash burning in the Cascades could be accomplished without getting smoke into the valley. Yet in their "Willamette Valley Metropolitan Area Air Pollutant Emission Inventory" (Hoffman 1970), the National Air Pollution Control Administration included all the slash burned west of the crest of the Cascades, east of the crest of the Coast Ranges, and in one county (Lane), east of the coast itself as slash in the Willamette valley. There is not necessarily a relation between tonnages emitted into the air over an area and concentrations at a specified level in a particular place.

WEATHER SITUATION

Air pollution potential is greatest when there is little wind and conditions for convective rise and mixing with a deep layer of air are unfavorable. These stagnant conditions can be avoided. They do not necessarily occur at all elevations simultaneously. Air stagnation is typical in low elevations--valley$, basins, flat country--at night. In the mountainous West, substantial winds often occur in the night and early morning hours across the ridges and peaks while only the gentle downvalley winds drift through the canyons. But these conditions vary with the weather situation as the fire-weather forecaster is well aware. The degree of stratification and the weather properties of each stratum vary. Because of this, terrain configuration has varying effects. These thermally separated strata can be effectively used to keep smoke away from levels where it is not wanted. Differences in stratification cause an airshed, so designated for a particular weather condition, to be of no significance in other weather. An effective burning and smoke management system must, therefore, be keyed to changing weather conditions, to local weather affecting a particular fire, and to weather in smoke-sensitive areas.

Local circulation patterns that reinforce low elevation air quality problems develop when combination of terrain and three-dimensional weather patterns are favorable. The Los Angeles basin diurnal system (Edinger et al. 1972) prevents polluted air from escaping through the persistent inversion. Similar maritime inversions are typical along the Pacific coast during the warmer months. Low elevation emissions become trapped, but high elevation sources are excluded by the same inversion. Lyons and Olsson (1972) describe a nearly closed system that develops in the lake breeze system near the shore of Lake Michigan. Large metropolitan centers, which act as heat sources, develop a weak convective circulation that below stable air tends to concentrate emissions in and over the city center.

SCALE

Most chronic air pollution problems are in metropolitan areas in basins or valleys subject to frequent periods of air stagnation. But the spatial extent (scale) of pollution problems runs from the heavy concentration of CO at the city's busiest intersection at quitting time to the global threat of increasing particulate and CO_2. The term "ambient air quality" can be applied to situations anywhere on this scale. Although the area and air layers affected by any given forestry burn vary by source, location, and weather, the effect on air quality needs to be considered in scale of pollution situation involved. A consideration in scheduling each burn should be the answer to the question, "What ambient air quality will I affect?" Intelligent management of air quality requires consideration of all scales. Whereas emphasis here is given to the horizontal dimension, a vertical dimension and a time scale are implied, though more variable. Scale names discussed below are adapted from the terms used for meteorological situations that dominate the distribution of emissions.

Microscale situations are up to 1 mile (1.6 km) in extent. They might involve the accumulation of smoke from a small fire in a ravine or other low place, particularly at night. An individual campfire is on this scale. Maximum vertical extent on the order of 100 feet (30.5 m) and duration of 1 or 2 hours would be characteristic.

Toposcale or local scale situations are up to 10 miles (16.1 km) in diameter and are controlled by larger topographic features. Many metropolitan areas characteristically have air quality problems at this scale with problem centers at the microscale. Nighttime valley accumulations of drifting smoke from residual slash fires, one or two mills, or from night emissions in a city are usually at this scale. Vertical extent of toposcale air quality systems would be less than 1,000 feet (305 m) with duration up to 8 hours. These situations are usually diurnal and are terminated by the heating and mixing of the air trapped below the nighttime inversion with higher layers and advection away by daytime breezes.

They do not form during windy weather. Toposcale accumulations may contribute to larger, longer lasting mesoscale accumulations and will be more persistent during cooler, more inversion-prone seasons of the year.

Mesoscale air quality conditions occur in major terrain basins and extend from the large metropolitan area to a contiguous area encompassing several metropolitan areas all essentially within the same meteorological and geographical influences. The Los Angeles basin, the San Joaquin valley, the Willamette valley, and the Puget Sound area frequently form mesoscale pollution systems. In all of these areas, a climatic factor, the maritime inversion, and the obstructing mountains form a lid and sides to the system (figs. 1 and 2). With a maximum height or ceiling nearly 4,000 feet (1,219 m) and a lateral extent nearly 150 miles (541 km), the mesoscale situation may last up to 2 weeks. Most of the concern with polluted air deals with this scale. These situations usually recur in the same areas and can be outlined on a map and in vertical atmospheric cross section with temperature analysis. These systems also depend on semi-stagnant wind and limited vertical air motion and are predominantly seasonal. They are terminated by increased winds or change in airmass in connection with changing synoptic scale weather patterns. Many of the recurring air pollution problems at this scale and most air quality regulations are aimed at the ambient air quality at the lower mesoscale or the toposcale. These systems do not exist during windy conditions which prevent accumulation of emissions in a limited volume.

Airmass or synoptic scale pollution occurs when air stagnates over a large source region possibly from many mesoscale pollution source areas for a week or more, each day acquiring more impurities that spread a bit deeper. This scale

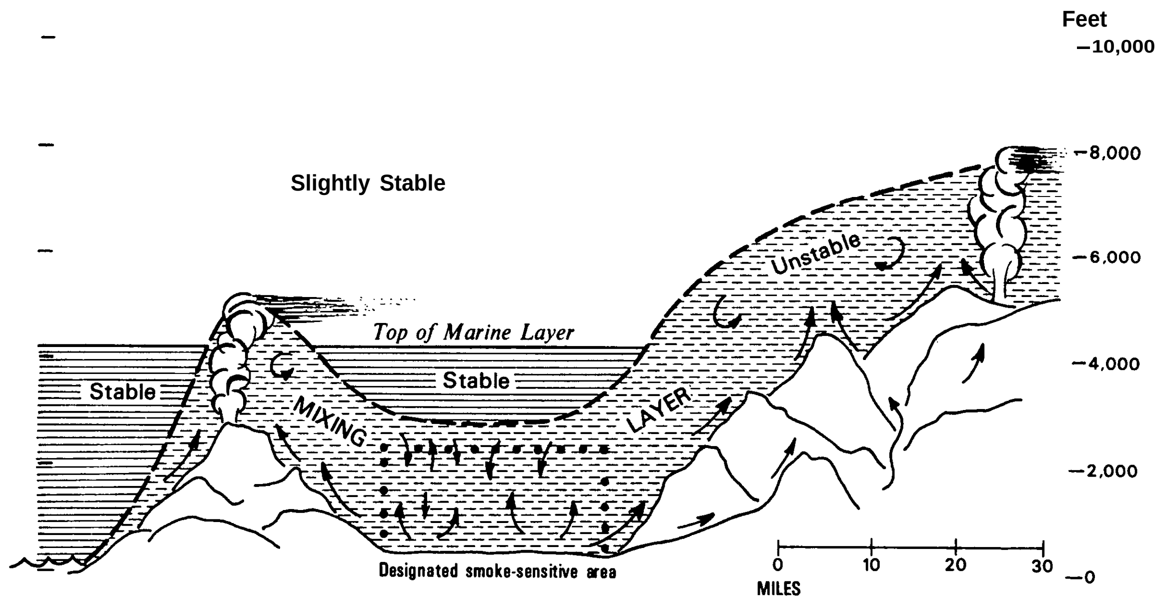

Figure 1.—Common mesoscale and local afternoon dispersion conditions ***west of*** *the Cascades during the warm season. The mixing layer is shallower in cooler seasons.*

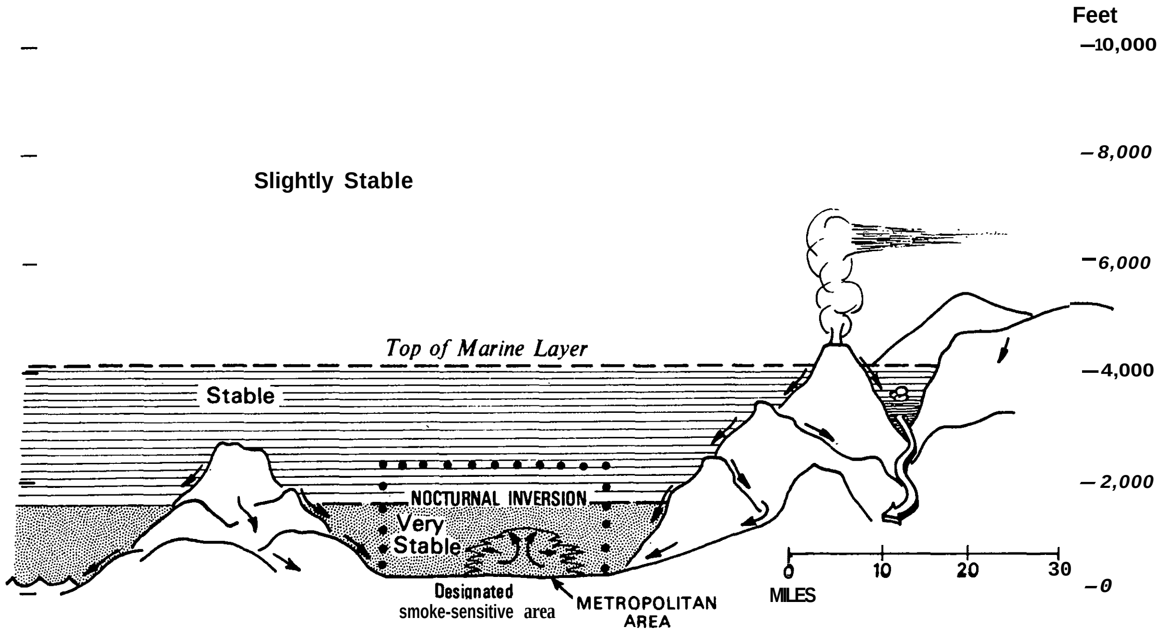

Figure 2.--Common nighttime or early morning condition during the warm season west of the Cascades. Downslope breezes develop on still, clear nights. Similar stratified conditions without downslope breezes may persist throughout the day during the colder seasons and during rainy weather.

may exceed 1,000 miles (1,609 km) in extent and may involve air layers throughout the tropopause, usually 25,000 to 50,000 feet (7,620 to 15,239 m). Airmass pollution conditions pass through two stages--the stationary or formative stage in the source region and the moving stage. The airmass may retain its characteristics for weeks. As it moves, it may pick up additional impurities so that by the time it has moved across the continent, it is visibly contaminated to the stratosphere. If the airmass is dry, the processes of agglomeration and fallout will be slow though the impurities may be dispersed as the airmass loses its identity, being transported at different speeds and directions at different elevations. If the airmass is moist or has a long trajectory over tropical waters and becomes moist, precipitation processes may be expected in which the particulate acts as condensation or ice nuclei and the resulting snow or rain tends to dissolve or wash out other particle and gaseous materials. The vast smoke clouds from forest conflagrations reach this scale and have been known to cross oceans (Plummer 1912) and move from one region to another. At this scale, smoke from Alaskan forest fires has covered the Pacific coast, and airmasses arriving along the Pacific coast from Asia have been noticeably brown. Air pollution on the airmass scale may influence cloud and precipitation processes in that particular airmass.

Hemispheric scale pollution has been observed in radioactive debris from tests of nuclear weapons. Eventually, the individual plumes diffuse and the contamination becomes general. There is little danger of this in the troposphere because the global circulation patterns sooner or 'later run the air through the scrubbing processes of precipitating weather systems. The stratosphere is above the weather, is stratified, and does not mix with the lower layers, hence would retain any impurities considerably longer. Though smoke components generally do not accumulate at the hemispheric scale, the contribution of CO_2 and particulate that appear to be increasing are of some concern. On the global scale, the contribution of forest burning to the overall CO_2 and particulate production is slight, hence must be proportionately slight to the long-term trend.

PURPOSES, TRADE OFFS, ALTERNATIVES

A decision to use fire to accomplish a resource or environmental management job is only one of a series of decisions in which the resource manager must weigh advantages against disadvantages of the alternatives available. With fire may come smoke, so the disadvantages of smoke must be outweighed by the advantages of fire over some alternative not involving burning. The kinds of values that should enter into the decision might include:

1. Short- and long-term impacts and risks.
2. Onsite and offsite effects.
3. Effects on other essential resources--soil, timber, water.
4. Risk of more serious consequences in the future.

TRADE OFFS

Perhaps some guidelines can be suggested for considering alternative forest residue treatments. A scale of importance of effect of treatment on the human environment might be attempted with the most undesirable effect at the top:

Clearly a safety hazard
Damaging to health
Damaging to life support; i.e., renewable resources--forests, grazing, soil productivity, agriculture
Damaging to property, plants, animals
Damaging to the basic nonrenewable. resources (soil)
Degrading to recyclable resources--air and water
Damaging to recreation and enjoyment

In addition, the damage or deleterious conditions should be classified by:

Permanence of effect	Visual or material effect
Certainty of effect or avoidability	Susceptibility to correction
Proportion of population affected	Emotional, economic, physical effects
Local or distant influence	
Cumulative effects	Time for recovery

As has been discussed, burning is not just a single uniform treatment--many variations are used. The composition of the emissions, the trajectory of the plume, the height of the smoke, the amount of time it remains in the air, its visual exposure, the duration of the source, all vary with the kind of burning. Careless timing or lack of consideration of other factors should not cause condemnation of the use of all fire; burning can usually be done without causing a nuisance. Regulations should be aimed at preventing the smoke nuisance, not at prohibition of the use of fire.

In weighing alternatives, if production of smoke nuisance is an important consideration, the characteristic kinds of smoke production by various burning procedures should be considered. These vary from almost no visible emission from open, direct-fed incinerators, to the possibility of burning covered piles during precipitation when the smoke will not only not be seen, but much of it will be rather quickly removed by precipitation nucleation and washout.

Flexibility of choice is essential here as in any other natural resource consideration with many factors involved and endless possible combinations of situations. The land manager must take into account the possibility of conflagration-type fire with its accompanying environmental destruction if he is unable to reduce accumulation of high hazard fuels to a reasonable level and keep it there. The consequences of a conflagration are tremendously greater than possible temporary annoyance from prescribed fire smoke.

The environmental resource manager must have a scientifically sound basis for making decisions on treatments. that affect the environment. He must be certain that he is not, for example, sacrificing long-term productivity and protection from destructive conflagration for a few hours of smokeless sky, the current balance of environmental law notwithstanding. Fire has been a part of the forest environment as long as there have been forests. Smoke has been in the atmosphere just as long. Managing all fire climax forests without fire may not be possible. To enable him to minimize undesirable impacts of both fire and smoke, the forester needs strong scientific backing for his residue management decisions.

CONCLUSIONS

NET EFFECT OF RESIDUES AND TREATMENT ON THE AIR RESOURCE

Concern for the air resource in making decisions about prescribed burning of forest residue should be only one of many concerns for the various resources and factors that comprise the forest environment. The most important air quality emergency from forest emissions and one that must be aggressively prevented comes from the catastrophic fire with its destruction of all forest resources with long-lasting effects. The small prescribed burns, designed expressly to prevent catastrophic fires, can be scheduled during weather conditions that assure smoke dispersal with minimum effect on air quality, particularly in smoke-sensitive areas. Indeed, extra effort should be made to remove excessive fuels under favorable dispersion conditions; fuel accumulation increases the likelihood of a conflagration and attendant extreme smoke conditions.

Existing air quality regulations designed for metropolitan area problems are not generally applicable to the usually remote, higher elevation residue reduction fires that often have sufficient energy to place their smoke plumes far above the layers of atmosphere that come in contact with the surface. Smoke behavior and dispersion depend on weather which is changeable and provides a great variety of dispersion conditions. Smoke management systems intensively using available fire-weather information match the dispersion condition to the burning job, hence can accommodate a considerable amount of prescribed burning without serious effect on air quality. Each prescribed burn should be considered on its merits with respect to convective rise, plume trajectory, elevation, and air quality impacts as well as from the standpoint of effects of the burn and alternative treatments on related resources.

Emissions from many prescribed burns can be minimized by specifying conditions that will produce least emission; i.e., driest fuel, hottest fire, soil-free piles, and shortest smoldering time. Where visible smoke is not tolerated, an open forced-draft incinerator may be used. Where quick removal is desired, residue piles may be covered for burning into a precipitating cloud system. Light underburns with little convective energy and the smoldering remnants of hotter fires cause the greatest problems for smoke management.

Large amounts of particulates and gaseous emissions originate from forestry residue prescribed burns. But the amounts themselves are not directly indicative of their importance. According to the U.S. Council on Environmental Quality (1973):

> The weight of air pollution emissions is only a rough measure of air pollution. Indeed, the geographic concentration of pollution sources and the dispersion of the pollutants once they leave the sources determine actual air quality. Also, weight does not take into account the effects of a pollutant.

This conclusion is particularly appropriate to judgment of the impact of forestry burning on air quality.

An entirely different emphasis would be justified for smoke from woody fuels if that smoke had demonstrably caused the problems for which air pollution is collectively blamed, such as damage to health, corrosion, damage to plants, or photochemical eye-stinging smog. But forest fire smoke has been in the air since forests were on earth; and after thoroughly examining the literature, wood chemist J. Alfred Hall (1972) concluded:

> I have found no evidence that involves the combustion products of forest fuels in permanent injury to human health.
>
> The sulfur content of wood is negligible....
>
> Hydrocarbons.. .are in large part similar to or identical with products of nature omnipresent in the environment. Only small traces of photochemically active compounds of low molecular weight are produced.
>
> As for carbon monoxide, evidence of increased concentrations at short distances from going fires is lacking.
>
> The temperatures attained in burning forest fuels are generally too low to permit formation of nitric oxide (except)...briefly in explosions of concentrations of flammable gases, especially in wildfires.
>
> Particulate matter..,. In their chemical nature...are probably indistinguishable from many components of the atmosphere, produced in normal natural processes.
>
> In general, the only penalty inflicted upon the environment by prescribed burning is a small and temporary decrease in visibility.

I have found no new evidence in more recent literature that would materially alter these conclusions, though Darley[14/] has found NO produced briefly in laboratory fires. This is not to deny that smoke is an annoyance and sometimes an obvious safety hazard. Foresters should, in time, be able to establish a balance characterized by minimum major smoke episodes and minimum nuisance from prescribed fire smoke. They will do this with hazard reduction, by fire where necessary and in conformance with a smoke management system that minimizes smoke concentrations in areas where it is intolerable. They will also take aggressive action to prevent the very large fires with extensive dense smoke over which there is no control. Because of present limitations on abatement of forest fuel hazards, there will likely be major smoke episodes and an increase in prescribed burning before this balance or equilibrium point can be reached. Because of improving utilization, alternative residue treatments, and increasingly effective fire suppression, such an equilibrium point will be well below the natural production of smoke from lightning fires and burning by Indians.

NEEDED RESEARCH

Many aspects of the presence of forest fuel smoke in the atmosphere are unknown and offer opportunities for research. A general need is for development of a decision matrix permitting selection of residue treatment method on the basis of effects on the complete environment over the short and long term. Treatments would include but would not be restricted to various forms of burning. Effects would include the impact of managed smoke. Considerable additional knowledge is needed to fill all the blanks in such a matrix. Some of the questions that need answers follow.

1. Specifically, how effective are precipitating cloud systems in removing particulate and gas components of forest smokes?

2. What are the important components in forest smokes from the major kinds of fuels in both flaming and glowing combustion; what processes are these components involved in under various atmospheric conditions and in mixture with other substances commonly found in the air; and what are their removal mechanisms?

3. What are the actual toxicological properties of smokes from the various forest fuels?

4. How can the field forester readily estimate the convective column strength he can generate from a given combination of: (a) fuel composition, loading, and arrangement; (b) fuel moisture condition; (c) size of area aflame; (d) wind profile; and (e) atmospheric stability?

5. What amounts of what atmospheric gases are taken up and released by various microbiota in the forest floor under diverse forest situations?

14/ Ellis Darley. Laboratory tests of combustion products from wood fue s. International Symposium on Air Quality and Smoke from Urban and Forest Fires Proceedings, Fort Collins, Colorado, Oct. 23-26, 1973 (in preparation for publ cation by National Academy of Sciences).

6. Can an index be developed based on weather factors and assuming constant emission of all usual sources that will indicate the level of air quality to be expected in a particular locality for given season and weather conditions? (Necessary for judging effect of intermittent nonpoint sources like forestry burning.)

7. What methods can be developed for predicting in more detail the diurnal patterns of stability and wind profile over wide areas of mountainous terrain for application to individual fire and smoke dispersion problems?

8. What are the details of some of the typical important weather situations that permit good smoke dispersion and of those that create smoke dispersion problems?

9. What is the normal balance of emissions to and uptake from the atmosphere of hydrocarbons, CO and CO_2, and nitrogen compounds in various typical forest situations?

10. What smoke dispersion coordination aids can be developed that will monitor and project plume locations and smoke densities in several strata and in air stagnation areas at the surface for routine use in scheduling burns?

SUGGESTIONS FOR REVISION OF CURRENT PRACTICE

Forest residue situations are evaluated primarily on the basis of esthetics and short-term air quality. An environmentally balanced decisionmaking process is needed that will permit evaluation of forest residue situations on the basis of such long-term environmental factors as risk of destructive fire, deterioration of forest production, and consideration of other resource, environmental, and economic values.

To avoid what seem to be inevitable serious smoke episodes from conflagration-type wildfires in areas where residue has been steadily increasing, a new program of aggressive hazard reduction including prescribed burning under smoke management is needed wherever such burning can be environmentally accommodated.

Smoke from rekindled or escaped prescribed fires needs to be eliminated; greater attention to soil-free piling, mopup, and wet season burning of covered piles is needed.

INDICATIONS FOR EQUIPMENT

Visible smoke has been a deterrent to the use of open burning as a residue treatment. A principal difficulty with prescribed burns, including pile burns, has been smoky glowing combustion from residual fire which incidentally also acts as a source of firebrands that may cause the unwanted burning of adjacent areas during and following dry and windy weather. Combustion with minimum smoke has come with the use of certain open pit or bin-direct-fed incinerators. The possibilities for improving pile burning by use of portable blowers, draft deflector walls, and chunking-in equipment should be investigated, particularly for use during the wet season.

RESEARCH IN PROGRESS

FOREST SERVICE

Fuel Treatment, Prescribed Fire, and Air Pollution, Southern Forest Fire Laboratory, Southeastern Forest Experiment Station, Macon, Georgia.

Includes studies in:
1. Production and quality of smoke
2. Smoke concentration and dispersion

Smoke Characteristics Program, Research and Development Program, Southern Forest Fire Laboratory, Southeastern Forest Experiment Station, Macon, Georgia.

Studies in effects of smoke from forest fuels on air quality.

Fire Control Technology, Northern Forest Fire Laboratory, Intermountain Forest and Range Experiment Station, Hissoula, Montana.

Includes study of relationships between heat output and smoke emission.

Fire Effects and Application, Northern Forest Fire Laboratory, Intermountain Forest and Range Experiment Station, Missoula, Montana.

Includes:
- Miller Creek-Newman Ridge prescribed fire study
- Influence of fire intensity on smoke movement
- Glowing combustion in decadent forest fuels

Environmental Systems--Interior Alaska, Pacific Northwest Forest and Range Experiment Station, Fairbanks, Alaska.

Includes: Occurrence, persistence, and associated visibility conditions of summertime wildfire smoke and haze in interior Alaska.

Forest Residues Reduction Program, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Effects of forest residues and their treatment on the air resource and on other components of the environment.

Cooperative Forest Fire Science, Pacific Northwest Forest and Range Experiment Station, Anderson Hall, University of Washington, Seattle, Washington.

Engaged in forest smoke related investigations through graduate student research projects and through cooperative research with the University of Washington including Colleges of Forest Resources, Preventive Medicine, and Civil Engineering.

Fire Chemistry, Pacific Southwest Forest and Range Experiment Station, Berkeley, California.

Exploration of fundamental chemical and physical processes of combustion and extinguishment.

Fire Meteorology, Forest Fire Laboratory, Pacific Southwest Forest and Range Experiment Station, Riverside, California.

Engaged in tracing the circulation of Los Angeles basin smog into forest areas and in determining its effects on forests.

OTHER RESEARCH ORGANIZATIONS

Other pertinent research is or has recently been underway at:

Washington State University, Pullman, Washington: College of Engineering, Air Pollution Research Section.

Oregon State University, Corvallis, Oregon: Air and Water Resources Center, and Schools of Engineering, Agriculture, and Science.

Statewide Air Pollution Research Center, University of California at Riverside.

Stanford Research Institute, Menlo Park, California.

Environmental Protection Agency

National Ecological Research Laboratory, Corvallis, Oregon.
Pacific Northwest Environmental Research Laboratory, Corvallis, Oregon.
Meteorological Laboratory, National Environmental Research Center, Research Triangle Park, North Carolina.
Technical Division Applied Science and Technology Research
Agricultural sources including forestry and logging activities.

Environmental Protection Agency contractors

Midwest Research Institute
425 Volker Boulevard
Kansas City, Missouri

Illinois Institute of Technical Institutes
10 W. 35th Street
Chicago, Illinois 60616

Forest fire emissions

Booz-Allen Applied Research
4733 Bethesda Avenue
Bethesda, Maryland

Alternatives to residue treatment by burning

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FIRE HAZARD AND CONFLAGRATION PREVENTION

Robert E. Martin and Arthur P. Brackebusch[1/]

ABSTRACT

Development of conflagrations is dependent, among other factors, upon weather, terrain, and Zarge accumulations of residue or fuel. Theoretically, by strategio manipulation of residues, the forester is able to trade routine cost of hazard reduction for cost of emergency conflagration suppression. He cannot control the weather or terrain. Fuels accumulate in natural systems, but man's actions may greatly modify the nature of the fuels and thus the hazard. Each fuel component has its own characteristics, thus making its specific contribution to hazard. Integration of fuel management planning with other phases of forest management planning will help to achieve a pattern of fuels and low hazard areas compatible with fire management and environmental objectives.

Keywords: Forest fuels--management, fire hazard reduction, conflagration.

INTRODUCTION

In this paper we consider forest residues as potential forest fire fuels. We will examine the fire properties of residues and discuss fuel management possibilities.

Organic materials accumulate when plants use the sun's energy and store this energy in the form of plant bodies and extractives. The rate of production, decomposition, and accumulation depends on many factors. To those of us concerned with fire in Pacific Northwest forests, important factors are the total amount of material accumulated, the amount available to burn under given conditions, and the configuration of these fuels. Configuration affects accumulation and available fuel as well as fire behavior.

In temperate regions, less than 1 percent of the sun's incident energy is converted into organic matter. In forested land this amounts to 10 billion

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calories (40 million Btu's) per acre (24.6 billion calories/hectare) per year (Geiger 1965, Beaufait 1971). Converted into more familiar units, this amounts to over 300 gallons of gasoline per acre (3,000 liters per hectare) per year (Reifsnyder and Lull 1965) or enough fuel oil to heat a small house in the Seattle area for 1 year.

Some of the sun's energy captured through photosynthesis is used in the vital processes of the plant. Much of it, however, is converted into organic matter that persists over varying lengths of time--flowers and foliage remain alive for the shortest time, the branches longer, whereas the main stems and roots of trees and shrubs remain alive longest. The aerial portions of herbaceous plants die completely each year. All parts of the plants, as Beaufait (1971) has stated it, eventually become waste products of their community, and the aerial parts fall to the ground to become part of the organic mantle of the forest. This material in the forest floor decomposes at varying rates, depending particularly on its inherent decay characteristics, temperature and moisture.

The rate of accumulation of the organic layer varies widely. In moist tropical environments, decomposition may take place almost as rapidly as material is deposited, so that accumulation in the forest floor is negligible. For the North Temperate Zone, Bray and Gorham (1964) developed a curve indicating an average annual accumulation rate of 3 to 4 tons per acre (6.7 to 9 metric tons/ha), a figure confirmed by Beaufait (1968) for the Northern Rocky Mountains. For 40-year ponderosa pine *(Pinus ponderosa* Laws.) on the east side of the Cascade Range in Washington, Fahnestock (1968) reported approximately 30 tons per acre (67 metric tons/ha) in litter and duff, indicating a rate of net accumulation somewhat less than 1 ton (2.24 metric tons/ha) per year. Net accumulation of forest fuels is a real concern that was explored further by Dodge (1972).

Regardless of the rate of production, without disturbance one might expect decomposition to eventually balance production so that no net accumulation of fuels in the forest would occur. After the initial fuel buildup that follows the death of a lodgepole pine *(Pinus contorta* Dougl.) stand, available fuels and fire potential may decrease for many years until the new stand begins to deteriorate.[2]

In many terrestial ecosystems, however, fire or other agents often intervene. In a fire, organic materials of the forest floor are largely consumed, and often other fuels are consumed such as needles, small branches, and dead standing snags. After the fire, deposition of materials to the forest mantle will often be accelerated as needles are cast and fire-killed woody branches and stems fall to the ground. The stems may stand for years and are a serious fire problem whether standing or fallen.

In any climate in which production of residues exceeds decomposition, fire is considered a normal part of the ecosystem. This is true in most of the northern latitudes except in very high rainfall areas (rain forest of the Olympic Peninsula) where large quantities of fuel may build up and reach an equilibrium in which decay rates and production rates stabilize. Occasionally, under extreme conditions, large fires will develop in these stands too; but they are not common.

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[2] G.R. Fahnestock. Forest fire fuels in the Pasayten River drainage of north central Washington. Paper presented at the 1973 meeting of the Northwest Science Association.

In most areas, fire frequency is fairly well established and directly related to the need for fuel removal and the natural risk that is available to start the fire. Lightning is a common fire starter in the Pacific Northwest, and prior to settlement by Europeans, the aborigines were also a source of ignitions.

If fire can be accepted as natural, we can begin to consider the aspects of fire as being part of the ecosystem. Fires begin as one or more small, usually controllable, fires. If they are not stopped in the early stages and if large quantities of fuel are available, under the right weather conditions, they can become conflagrations. Conflagration, by definition, is a large and destructive fire that releases energy at such a rate that man cannot supply enough energy to influence or limit its spread.

If man wants to achieve his management objectives, he must be able to deal intelligently and effectively with fire at all stages of its development. His greatest opportunity for successfully managing fire is by influencing the quantity, nature, and distribution of fuel available for combustion.

Historically, as fire control organizations have grown, they have become more efficient, effective, and powerful. Thus, they have been able to control larger and more powerful fires. But finally, an even larger and more powerful fire system overwhelms the control organization. Suppression activities themselves often preserve the available fuels by suppressing or delaying the runaway fire. With the increased fuel load, the next fire may stand a better chance of escaping fire control organizations.

In this paper we approach the problem of conflagration through fuel management--manipulation of living and dead vegetation to enhance man's ability to influence wildfire. Of the factors influencing fire--fuel, weather, and topography--fuel is the only one over which man can exert extensive influence. Through large expenditures, he can modify only slightly either weather or topography, but he has opportunities for conflagration prevention through fuel management.

We will discuss first the fundamental characteristics of fuel particles and fuel beds. Then we will cover various fire characteristics of fuels, the fuel situation in the Pacific Northwest, the biological aspects of fuels, and finally, fuel management.

FUEL PROPERTIES

Since we have said that the production of fuel is a natural process, it is then not realistic to differentiate between natural and manmade fuels. Man's primary influence is that of changing the timing, rate, and nature of fuel accumulation. Through forest harvest he may create a hazardous fuel situation much sooner than if the stand remained undisturbed. He may also change the character of fuel by creating concentrated slash near the surface where there were previously only elevated green crowns. Since man's primary influence is to change the physical properties of fuel, therein also lies his greatest opportunity to control and manipulate the distribution, timing, and nature of fuel.

Component fuels— the fuels of different sizes and properties--have individual characteristics which contribute to an overall fire problem. Although in practical situations we can seldom consider one component separately, an awareness of the contribution of each to fire hazard can aid us in making decisions on land management practices. For example, should our efforts in hazard reduction be for reduction of litter, removal of brush, or felling of snags? All three may be present on a given site, and each has its particular fire characteristics. The appropriate treatment of residues to reduce fire hazard depends on the individual components.

The primary characteristics of fuel elements that influence fire behavior are physical and chemical properties, moisture content, and size.

Moisture and heat transfer take place through the surface of a fuel particle. Consequently, the nature of the surface and the density of the fuel have a great bearing on controlling the rates of exchange of heat and moisture.

Chemistry is further important because there is evidence that certain salts can inhibit flaming (Tang 1967; Broido 1966; Philpot 1968, 1970). This principle is used in fire retardants. Certain plant fats and oils volatilize easily and produce combustible gases at relatively low temperatures. In some fuels, such as Douglas-fir ***(Pseudotsuga menziesii*** (Mirb.) Franco) and chamise ***(Adenostoma*** sp.), the amount of fats and oils in foliage increases during the summer (Philpot and Mutch 1971), a process that increases their flammability. Fats and oils may be a major factor in susceptibility of vegetation to crown fires.

Moisture content may be the most important single property controlling flammability of a given fuel. It reflects the wetting and drying influences of weather and can change rapidly. One way moisture affects the combustion process is by cooling action. Heat energy is required to raise the temperature of water to the boiling point to separate bound water into vaporized water. It also smothers fire. Water vapor driven from the fuel displaces oxygen--a noncombustible mixture is the result. When moisture contents reach certain levels, ignition and spread of fire are prevented.

Limiting moisture contents depend on fuel characteristics and intensity of heat source. Moisture contents of 20 to 30 percent are limiting for initiating fires (Anderson 1969). Moisture contents over 100 percent are not limiting for crown fires. Moisture contents fluctuate diurnally, primarily in lighter fuels. They also fluctuate seasonally between periods of rain and of drought. Seasonal droughts common in the Northwest create drier fuels causing a greater potential for high intensity fires. Logging slash in the summer sun dries to 10-percent moisture content in 2 to 3 weeks. Fully shaded slash may take more than 6 weeks of drying to reach 10-percent moisture content.

New green conifer foliage on the tree has a moisture content of about 200 percent which drops to about 120 percent by late summer, whereas old live foliage on the tree increases from about 100 to 120 percent through the summer.

Moisture contents below 100 percent do occasionally exist for living fuels. Fine herbaceous materials and grass cure during the summer, becoming especially dry and highly flammable.

A timelag concept is useful for categorizing fuels. It describes the rate that the fuels lose moisture to or gain moisture from surrounding air. Fine fuels have short tirnelags which means they dry rapidly compared with large fuels.

Timelag constant is the time it takes for a fuel to lose 63 percent of its moisture above the equilibrium moisture content under standard drying conditions. Equilibrium moisture content is the moisture content at which dead fuels neither gain nor lose moisture with time. This occurs when the vapor pressure of moisture in the air and the fuel are equal. Fuel constantly moves toward equilibrium moisture content but, due to fluctuating atmospheric moisture, seldom reaches it. Timelag constant generally increases as fuel size increases. Dead grasses have a timelag of less than 1 hour; some fine grasses, as short as 10 minutes. A %-inch twig has a timelag constant of about 1 hour. A 3- to 4-inch branch has about a 10-day timelag. After three timelag periods have elapsed, 95 percent of the moisture above the equilibrium moisture content will be removed from drying fuels under standard drying conditions of 80° F (44° C) and 20-percent relative humidity. The field behavior of fuels of various timelags have been described by Fosberg et al. (1970) and Fosberg (7971).

Particle size is a vitally important characteristic of fuels. It is usually expressed as thickness or the ratio of surface area to volume. Thin particles have large surface to volume ratios. Consequently, they have large areas to transfer moisture and heat during the combustion process. As particles become thicker, their surface to volume ratios decrease. This ratio is important because it relates *to* heat and moisture exchange. Small particles dry out and ignite quickly because their large proportion of surface area to volume permits rapid exchange of moisture and heat. Generally, as fuel particles become larger, up to some large branch sire, more time is required for ignition. Fire spread is really a series of ignitions. Thus, fine fuels support higher rates of spread than large fuels because they ignite faster.

FUEL BED PROPERTIES

The characteristics of. the fuel bed itself are of equal or greater importance than individual particles: (1) fuel quantity or loading expressed as tons per acre (metric tons per hectare), (2) compactness and porosity, and (3) continuity and distribution.

Light annual grasses may constitute a fuel loading of from ¼ to 1 ton per acre (0.56 to 2.24 metric tons/ha). Forest floors frequently have from 5 to 20 tons per acre (11 to 45 metric tons/ha) of duff and litter; Douglas-fir and western redcedar *(Thuja plicata)* slash, from 20 to over 200 tons per acre (45 to 450 metric tons/ha).

Quantity of fuel determines potential fire intensity, one of the most important factors in planning control of fires. High intensity fires occur in heavy accumulations of fuel and are difficult *to* control. Spotting and crowning are spawned by high intensity fires. Quantity alone, however, ***does not*** indicate what fuel is available for combustion. Fuel availability depends also on moisture content, size and compactness, and fire intensity; the ratio of living to dead fuels is also important. Living understory vegetation can hinder the spread of low intensity fires but is no hindrance to high intensity fires. Increasing fuel quantities sometimes means higher rates of spread, but spread potential depends greatly on other fuel properties.

Compactness and porosity refer to the crowdedness of particles. Highly compact fuels have a low porosity. Compactness influences the drying rate of fuels. When fuel particles reach a certain compactness, ventilation in the fuel bed is restricted and drying proceeds more slowly. For example, a single pine needle suspended in the air by itself has a timelag constant of about 1 hour, but the forest floor which contains large numbers of similar needles may have a timelag constant of several days.

Compactness affects rate of combustion. Combustion occurs at a maximum rate when particles are close enough to receive intense heat radiation and convection from adjoining, burning particles but not close enough to restrict flow of oxygen to the burning fuels or to shadow the radiant energy from burning particles. Rate of combustion could be reduced either by spreading or by compacting fuels. In practice, it is best to compact fine fuels and spread large fuels. Certain physical characteristics of vegetation determine compactness of fuel. For example, long pine needles create a more porous fuel bed than short fir needles because long needles support one another. Branching habits of tree limbs also will affect compactness both in the crown and in the resulting slash.

Continuity refers to the patchiness of fuels. Distribution is a loosely used term that refers to arrangement of fuel, horizontally and vertically. Continuity partly controls where fire can go and how fast it travels. A continuous distribution of fuel into conifer crowns enhances the likelihood of vertical involvement and crown fires. Firelines, ridges, talus slopes, streams, lakes, roads, and certain vegetative stands serve as breaks in horizontal fuel continuity. These discontinuities can be created by design with proper understanding of fuel management.

FIRE CHARACTERISTICS OF FUELS

Forest fuels have certain characteristics that govern the degree to which each component might contribute to fire behavior and, under certain conditions, to a conflagration. The various characteristics of a fuel component comprise its contribution to fire hazard. According to Anderson (1970):

> Ignitibility is defined as the ignition delay time. Therefore, at any specific source intensity, the most ignitible fuel is the one that ignites in the shortest exposure time.
>
> Ignition is assumed to occur when the fuel begins to generate heat or when flaming or glowing combustion is evident. In the latter case, greater variability can be expected. The time to ignition, the dependent measure, is a function of the stated properties of the fuel and the intensity of the heat source. With a heat source of 950° C, all fuels inspected ignited in about one second or less.
>
> . . . Flammability implies more than just time to ignition. I have considered flammability to have three components: ignitibility, sustainability, and combustibility.
>
> Ignitibility, the first consideration, has been described. Sustainability is the measure of how well a fire will continue to burn with or without the heat source. The method for describing sustainability in terms of fuel properties has not yet been formulated. Conceptually, the measure could be related to how stable the burning rate remains.

Combustibility is the reflection of the rapidity with which a fire burns. Again, the parameters to be used have not been determined, but they will be correlated to the specific burning time of a fuel. Specific burning time is defined as the weight of the test sample divided by the maximum burning rate. Conceivably, for some fuels, sustainability and combustibility could be the same.

The concept.. .(of fuel characteristics)...is directed toward individual fuel elements, although field problems are more concerned with the fuel continuum. To amplify, ignitibility of a fuel continuum would still be governed by the ignition of fuel elements; sustainability would be more closely associated with the rate of spread; and combustibility would be the intensity of the fire or its rate of burning.

These three features of flammability can be combined to give an overall appraisal of fuels. With proper interpretation of fuel properties, thermodynamics, and thermochemical processes, we can develop a comprehensive, but flexible, reference for appraising the fire potential of forest fuels.

IGNITIBILITY

The beginning stage of fire is ignition. Thus, ignitibility, the ease with which fuels are ignited, is the first consideration in evaluating fuel hazard. In effect, ignitibility depends on a particle of fuel being dried and raised in temperature to the ignition point, considered to be about 380° C or 716° F (Deeming et al. 1972). According to Brown and Davis (1973), this would be glowing combustion with flaming combustion occurring between 800° and 900° F (426.7° and 482.2" C), which probably corresponds to the ignition temperature of gases distilled from the fuel. Whether or not ignition occurs depends on the ability of the ignition source or firebrand to deliver energy to a part of the fuel particle and on the competing processes to dissipate the heat energy to the surroundings as well as into the particle itself. The moisture contained at that point is evaporated and moved, some of it into the surroundings and some internally. At the same time, the temperature of that point begins to rise.

Low heat conductivity is strongly and directly related to density. Low density wood materials such as punky, rotten logs are easily ignited. Fine particles such as needles, leaves, or slivers are also easily ignited as they have little ability to conduct heat away from the point being heated.

Generally, the fine components are the first to ignite at any point in a spreading fire. These fuels fit in the 1-hour timelag class of Fosberg and Deeming (1971) (1/8-inch diameter, Fahnestock 1970) and thus will respond rapidly to changes in humidity or to wind bringing drier air in intimate contact with the fuel particles. In loosely packed fine fuels, such as standing grass, fire may burn readily with only an hour or so of drying in sun and wind following a rainstorm.

Generally, fires start in the fine fuels (although dry rotten wood in a log may begin glowing combustion even more readily). Loosely packed fine fuels produce extremely high rates of spread and are termed flash fuels. Fine fuels compose much of the litter layer and are also present as small twigs, needles, and leaves remaining on dead or living branches. Needles, particularly, may be present as drape over larger fuels, serving to ignite the larger fuels and to spread fire vertically and horizontally. In addition, dry coniferous foliage may provide more heat per pound than many fuels due to a high content of resin.

Logs on the ground may at first be solid and covered by bark. The bark, and lichens on it, may be easily ignitible when dry. The fresh sound wood of the log would not at first be easily ignitible. As decay sets in, however, first the sapwood and later the heartwood becomes punky and easily ignited when dry. When logs and snags are quite dry, short-term rains may wet little more than the surface and the entire log or snag may return quickly to a dry and flammable condition. After a fire, logs and snags often contain holdover fires smoldering within rotten, punky wood. For this reason, logs and snags require extensive mopup work to detect and extinguish any sign of fire. The propensity of rotted logs and snags to hold fire makes use of fire in forest management more expensive and treacherous, as the fire may later be fanned and embers scattered into ignitible fuels.

Another factor in ignitibility is chemical composition. Our information on this aspect of ignitibility is incomplete. Some foliage contains volatile waxy and oil substances that may enhance combustibility (Philpot and Mutch 1971). Some mineral components, on the other hand, may hinder ignition and burning of woody fuels (Philpot 1968, 1970).

RATE OF SPREAD

Rate of spread (ROS) is a measure of activity of a fire in extending its horizontal dimensions (Forest Service Handbook, FSH 5109.12). It may be measured in terms of advance of the fire front (chains per hour), increase in fire perimeter (chains per hour), or increase in area (acres per hour) or in metric counterparts. Each of these has its particular usefulness in estimating where the head of the fire will be at a given time, the amount of fire line to be constructed and, thus, the effort required, and the area that will be burned, respectively. Since fire spread is a series of ignitions, it depends on size, type, amount, and compaction of fuel, and on fuel moisture content. It further depends on other conditions such as wind, slope, temperature, and humidity. ROS can be expected to increase with an increase in fuel loading per area, windspeed, slope, and temperature. ROS will decrease with increases in fuel size, moisture content, and humidity. ROS will increase with increase in fuel bed compaction, reach a maximum, and decrease again as the fuel becomes tightly packed.

One conclusion from "Mechanisms of Fire Spread, Research Progress Report No. 2" (Anderson et al. 1966) is:

> This study strikingly demonstrated that a large percentage of logging slash is limbs and trees of small diameter. The fuels that propagated the main forward spread of fire--needles and branches one-fourth inch and less in diameter--accounted for more than one-third of the dry weight of slash in the lodgepole pine and Douglas-fir plots.

Brown (1972) reports on the fuels supporting the flaming front of experimental fires in prepared fuel beds. Fires were extinguished with water fog after the rear of the propagating flame passed. He found:

Fuels less than 1 cm. in diameter accounted for half of the total weight loss even though this size material was less than 30 percent of the total loading. Fuel greater than 3 cm. in diameter provided only about 10 percent of the total weight loss in the flame front. No change in diameter was observed for particles of this size.

For slash and other fuels containing a similar mixture of particle sizes, our findings indicate that only the fine fuel components, essentially particles less than 3 cm (about 1 inch in diameter) supply the energy that characterized propagation of the spreading flame front. A generalization of this statement for all fuels likely would be incorrect. Different proportions of fine fuels probably correspond to different diameter limits for the component contributing most of the energy to the propagating flame.

ENERGY RELEASE RATE

Complete combustion of woody fuels yields about 7,800 to 9,200 Btu/lb (4,300 to 5,100 cal/g) of fuel burned (Byram 1959). Generally, pitchy fuels will have a heat of combustion on the upper end of the range due to the high heat of combustion of pitch (15,000 Btu/lb--8,333.2 cal/g). On a forest fire, however, combustion is incomplete as evidenced by the smoke emitted.

The energy release rate on a fire would be the amount of fuel consumed per unit of time, times the heat of combustion, times the efficiency, which would be a factor less than one. The amount of heat released may also be given in terms of energy release rate per unit area.

Energy release rate from the head of a forest fire may be an important factor in containing it. With a relatively constant combustion efficiency, energy release rate from the head of a fire depends on the rate of spread (in area) of the head times the amount of fuel consumed within the head. Thus, fuel loading becomes important. Normally, fine, small, and medium fuels will be consumed in the head as will the outer portions of large fuels.

EMBER PRODUCTION AND SPOTTING POTENTIAL

As the energy release rate in the head of a fire (or per unit area) increases, air velocities greatly increase. Indrafts and updrafts may become violent. The increased velocities enable the convection column to lift larger embers and to carry them faster and farther. Size of ember is important because larger embers have a longer burnout time and a greater heat source for igniting new fuels. Increased drafts have a multiplying effect on ember production. The drafts may topple snags or break loose large dead limbs. Impact of these with the fuel bed or ground may introduce a cloud of embers into the updraft, also increasing spotting potential.

An extreme example of increased velocity is the fire whirlwind. This tornadolike phenomenon may increase horizontal and vertical velocities in its vicinity severalfold (Byram and Martin 1970), thus increasing ember production and spotting potential. Formation of fire whirlwinds is favored by unstable atmospheric conditions, wind eddies, and greater energy release rate (Graham 1957, Byram and Martin 1970, Countryman 1971). Thus, reducing fuel loading is one way for foresters to reduce chances of whirlwind formation.

RESISTANCE TO CONTROL

Resistance to control is the relative difficulty of constructing and holding a control line (Society of American Foresters 1958) (FSH 5109.12, p. 70-25) and depends on difficulty in control-line construction and on fire behavior. Fuels enter into both factors. Fire rate of spread, energy release rate, and spotting potential are all directly related to the amount of readily combusted fuels. Resistance to line construction is directly related not only to the amount of fuel but also to the type of fuel, which may consist of logs, heavy brush, or slash which hinder progress of tractor or hand crews.

DAMAGE POTENTIAL

The potential for a fire to damage the environment, such as to a stand of trees or to the soil and watershed, is increased as fuel loading builds up. Many tree species, once the stems are of sufficient diameter, can withstand a low fire creeping through the forest litter of needles, leaves, and twigs. If fuel is allowed to accumulate, wildfire intensity may be expected to increase and the same trees may be killed or damaged due to the excessive heat transferred to the stem or crown. Excessive ground fuels can be safely removed by prescribed fire--fuel, weather conditons, and burning technique are prescribed so that only part of the fuel is removed at one time by a low intensity fire. Fire intensity and heat are limited to the tolerance of the aerial portions of the tree as well as the shallow root systems.

When heavy concentrations of residues burn, there is greater likelihood of damage to the site. Details of fire effects on soil are discussed by Moore and Norris (1974) and Rothacher and Lopushinsky (1974). Hot fires kill and consume shallow root systems, destroy organic soil compounds, and leave excessive ash which may disrupt soil biota (Bollen 1974). Through these effects, the protecting cover of litter and duff may be removed, opening the way for erosion. Soil structure may be destroyed. But the right amount of fire may be prescribed that will not have serious effects on the site and will reduce the hazard and potential for disastrous wildfire.

CONFLAGRATION POTENTIAL

Conflagration potential can basically be traced to three variable factors: fuels, weather, and ability to man fires. Topography is a constant in any given location. Of the variable factors, the land manager today can strongly influence all except weather.

1. Fuels. Conflagration potential may be considered high if there is a heavy loading of available fuel that may be expected to provide embers for spotting when fire burns at high energy release rates. The land manager can reduce fuel loadings by stand manipulation, by requiring more complete utilization from harvesting, and by fuel hazard reduction through vegetative manipulation, prescribed fire, or by chemical or mechanical treatment.

   Fuel or residue management needs attention early in the preparation of forest management plans to avoid contiguous areas containing high loadings of dangerous fuels that contribute to conflagration potential. Provision is needed for proper fuel reduction in any given forest operation, and for separation of high hazard areas to prevent fire spread from one to the other.

2. Weather. Weather is an important factor in any fire situation, and one over which man has little, if any, control. Long periods of dry weather increase the available fuel on any area. Starting with no available fuel in early spring or after a prolonged rain, the amount of fuel available to burn under given conditions will increase, generally until the next wet spell, and at the end of a long summer drought may include ,essentially all the surface fuels.

   Historically, conflagrations have developed during transient periods of severe fire weather--low humidity and high winds. The fire starts may also be of weather origin--dry lightning storms. These conditions must be expected.

   The manager must consider day-to-day as well as seasonal weather. At all times, when working with high hazard fuel areas, he should be constantly aware of the likelihood of potential conflagration weather by maintaining close liaison between his fire management people and the appropriate fire-weather forecast office. The same vigilance is necessary during any burning operation.

3. Ability to man fires. Most fires burning in fuels with the potential to produce conflagrations are controlled by efficient fire control organizations. Although we decry our acreage losses each year, our ability to control most fires to small acreages contributes to excessive fuel buildups that increase conflagration potential. These fuel buildups in many areas were at one time reduced by lightning or man-started fires; our policy of fire exclusion in all situations has allowed natural fuels to accumulate. The policy has been to man all fires; recently, a change is apparent toward letting fires burn under surveillance if they are accomplishing the objectives of prescribed burning.

   The ability to man fires varies with the season and with other fire activity--locally, regionally, and nationally. With a large number of fire starts, as so often occurs from dry lightning storms, avoiding conflagration depends on putting out fires while they are small. But heavy deployment of initial attack crews depends on availability of fire crews. The number of crews available locally depends not only on their use on other fires but also on predicted lightning and high fire danger.

   Manning to reduce conflagration potential also depends on accessibility and opportunity to accomplish effective action. Fuel management that provides fuel breaks in strategic locations can greatly enhance manning effectiveness.

FUEL SITUATION IN THE NORTHWEST

There is a wide range of variation in the fuel complexes of the Pacific Northwest, from the light annual cheatgrass of eastern Oregon and Washington, to the pine and mixed pine stands of the higher ranges of eastern and central Oregon and Washington, to the heavy old-growth Douglas-fir, redcedar, and hemlock (*Tsuga heterophylla* (Raf.) Sarg.) stands of the Cascade and Coast Ranges. Besides natural fuel complexes there are those that are disturbed by man through harvesting, thinning, roadbuilding, powerline construction, and the like. The amount and kinds of residues present in old-growth Douglas-fir forests were summarized by Cramer:[3/]

> The amount of logging slash varies greatly from one stand to another. The differences are caused by variations in stand age, defect, size and volume of associated species, market, sale basis, logging equipment used, hauling distance, and probably other factors. In old-growth Douglas-fir the amount of fine material 3 inches in diameter and 3 feet long and smaller doesn't vary greatly with changing market conditions. This small material was estimated by Munger and Matthews (1941) to average some 64 cords per acre based on 6 plots in which this material varied from 37 to 114 cords per acre. McArdle [1930] estimated that 95% of this material is consumed in the average slash fire. At 40 cu. ft. of solid material per cord and 30 lbs. of oven-dry woody material per cu. ft., this amounts to 36.5 T/A of small material consumed by slash burning.
>
> A slash fire also consumes a substantial portion of larger material. In the usual unmanaged old-growth Douglas-fir stand, there is considerable cull material both standing and already down. On the Willamette N.F. approximately 1/3 of the gross volume is cull. Net volume runs around 50 M per acre, leaving 25 M cull. This material might convert to 2 cords per M, or 50 cords of cull per acre. In addition there is the large material already on the ground which could easily run 12 cords per acre. The total, then, compares with the 62 cords of large pieces of waste wood per acre found by Munger and Matthews. McArdle estimated that no more than 30% of this material would burn in the average slash fire. Assuming 90 cu. ft. of solid wood and bark per cord and 30 lb. of oven-dry woody material per cu. ft., some 25 T of the 83.5 T of heavy material present would be consumed.
>
> In addition to the small material and the larger cull wood left after logging, there is considerable other material that burns in a slash or wild fire. Organic material on the forest floor (litter and duff) runs 10-30 T/A in 100 yr. old. D. fir in the Oregon Coast Range (Youngberry [Youngberg], 1966). Presumably there would be more in old-growth stands. Though some of this might be buried in the logging process, some 10 T/A might be consumed in a slash fire.
>
> In summary, for clear cut old-growth Douglas-fir slash:

	Combustible material present	Consumed by slash fire
Fine slash	38.5 T/A	36.5 T/A
Cull material	83.5	25.0
Forest floor	20.0	10.0
TOTAL	142.0	71.5

3/ Owen P. Cramer, logging slash in old-growth Douglas-fir. Report on file at Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, 2 p., 1967.

Gratkowski (1974) calculated that potential brush and weed tree residues from brushfield reclamation and conversion of hardwood stands could exceed 240 million tons (218 million metric tons), dry weight. He further estimated that at least 150 million tons (136 million metric tons) of residues must be burned or otherwise disposed of during brushfield reclamation and type conversion in the Pacific Northwest.

Recent detailed information on logging residue in the Pacific Northwest has been assembled by Howard (1971, 1973) and Dell and Ward (1971). Dell and Ward sampled the total volume of residue pieces 4 inches (10.2 cm) in diameter and larger on 27 clearcut units scattered throughout the Douglas-fir region. With an average of 7,430 cubic feet per acre (520 m^3/ha), gross volumes of this material varied between 32 and 227 tons per acre (72 and 508 metric tons/ha). The greatest amount was found in western redcedar logging on the Olympic Peninsula. The chippable portion, measured on 17 of the sampling sites, ran from 21 to 100 tons per acre (47 to 224 metric tons/ha). This averaged 45 percent of the material measured.

Howard (1973) collected data on 76 clearcut areas throughout Oregon, Washington, and California. He found approximately 4,500 cubic feet gross residue per acre (314 m^3/ha) remaining with 1,500 cubic feet per acre (105 m^3/ha) on private land. At least some of this difference is due to the greater proportion of National Forest cutting in old-growth, more decadent stands that yield more residue per acre than young-growth timber. Another factor is that private companies operating on their own lands receive all the benefits from hazard reduction and site preparation efforts, thereby providing economic incentive for removal of submarginal logs. In the ponderosa pine region, volumes were much lower, with the National Forests averaging 356 cubic feet per acre (24.8 m^3/ha) gross compared with 396 (27.6 m^3/ha) for private land.

A Region 6 Fuels Management Note (February 13, 1973) summarizes the residue fuel situation in Region 6 National Forests:

Residue problem	Area needing treatment	Estimated cleanup cost (Dollars)
Roadside fuel	4,702 miles	24,826,560
Old logging slash	155,060 acres	20,621,655
Thinning slash	116,595 acres	8,600,775
Total		54,048,990

Sampling of four National Forests in the Fuels Management Note indicated that 45 fires 10 acres and larger that burned where fuels had not been treated burned a total of 78,400 acres (31,870 ha); whereas it was estimated they could have been held to just over 32,000 acres (13,000 ha) had fuel treatment been practiced. Damages, respectively, were estimated at $184 million versus $71 million, a difference of $113 million. Fuels treatment (presumably for only the areas burned) would have been about $2.5 million with a benefit:cost ratio of 45.2. Since we do not know which areas will have fires, our treatment would have to cover much greater area, thereby greatly reducing the benefit:cost ratio.

BIOLOGICAL ASPECTS OF FUEL ACCUMULATION

In discussing fuel complexes, one should keep in mind the cyclic nature of vegetative types or stages in any area (fig. 1). Thus, the old-growth overmature stand may be farthest removed timewise from the burn that generated it; however, burning and regeneration may be the next stage in the area.

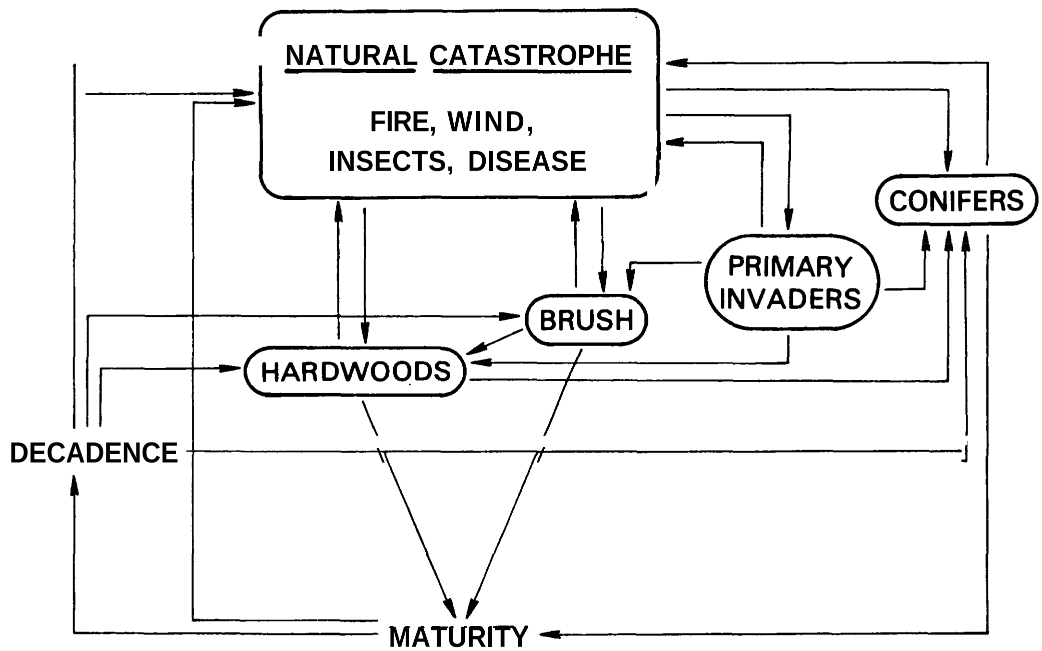

Figure 1.--Cyclic nature of forest biosystems. Although the stages through which an area passes may vary, basically the system can or will return to a previous stage.

We might trace fuels throughout the development of a hypothetical stand. Variations occur in species, site, and location.

First, let's categorize our fuels. Byram (1959) separated total fuel into available and residual fuels. Available fuel is that which is consumed under given burning conditions. Size, location, and moisture content of the fuel as well as fuel bed configuration and weather affect fuel availability. Generally, fine and small fuel particles in the forest floor are most available. Living tree trunks are probably least available. The fuel remaining after the fire is the residual fuel. The sum of available and residual fuels is total fuel. For this discussion, all organic matter above mineral soil in the stand is considered total fuel.

Fuel may be further separated by vertical position. Davis (1959) uses the categories of ground fuels and aerial fuels. Ground fuels are organic combustible materials from the surface of mineral soil to 6 feet (1.83 m) above ground. These fuels comprise the organic soils or soil layers, the forest mantle of duff and litter, as well as grasses, small shrubs, and the portions of larger vegetation less than 6 feet above the ground. Aerial fuels include all burnable material more than 6 feet above ground--the upper portions of trees and large shrubs, snags, and all the foliage and epiphytes on them.

Another category is "ladder" fuels, those that furnish the way for fire to climb from the forest floor into tree crowns. Ladder fuels may be either ground or aerial fuels.

Let's begin with the establishment of a northwest mixed conifer stand after a natural catastrophe--fire, wind, or insect or disease epidemic (fig. 2). Large amounts of freshly killed material remain, particularly as aerial fuel, whereas most of the older dead fuel was consumed by fire (or remains on the ground after other catastrophes). Wind puts most of the fuel from standing trees on the ground, but other catastrophes leave the dead trees standing. Over a period of years, the dead trees shed needles, then smaller twigs, followed by larger branches and bark, and finally the stem topples.

Within a few years, conifer reproduction becomes a significant fuel component. Buildup of herbaceous or grassy fuels as well as conifer needles from the young trees is sufficient to carry a fire that could kill the reproduction and consume the finer parts (fig. 2, c and d). The fuel buildup is supplemented by the falling of ever larger fuel components from the dead overwood (fig. 2, e and f). Fahnestock (see footnote 2) has shown that in lodgepole pine in the Pasayten Wilderness Area, the tendency is for ground fuels to increase for 40 years, then decrease until decadence of the stand sets in after about 150 years. His data might be considered an extension of the time frame of figure 2.

If fire does not occur, the reproduction enters the pole stage. Since overstocking is a relative situation, the well-stocked seedling stand may become an overstocked pole stand and thinning must occur to avoid stagnation. By now, much of the flashy herbaceous or grassy fuel has disappeared. Some shrubs which are not particularly flammable, such as salal (*Gaultheria*) and huckleberry (*Vaccinium* spp.), may be present as well as ferns. Large debris--branches and stems--falls from the dead overwood, and some tree trunks also fall. The poletimber is actively pruning itself of lower branches and building a layer of litter on the ground. Production of surface fuel exceeds decomposition,, so fuel builds up. Due to overcrowding, insects, and disease, many dead stems appear in the stand, contributing to fuel accumulation. Wildfire at this time would kill much of the stand under severe burning conditions, and the site might revert to an earlier successional stage. A creeping fire under moderate burning conditions in some species might do little damage and have desirable effects. Fuels would be reduced, lessening the chances of later catastrophic fire. Further, thinning of the stand might be accomplished, providing better growth potential for the remaining trees.

If survival of the stand is assumed, with adequate thinning to prevent stagnation and early stand deterioration, the trees continue to grow. The stems prune themselves, adding to the surface fuel of needles, shrubs, ferns, and other plants. If stocking has been sufficient, the crown is quite removed from surface fuels, reducing the possibility of fire climbing into the crowns.

Stands pass into the mature stage, and the trees are less susceptible to fire due to larger diameter and thicker bark. The crowns are farther removed from surface fuels, reducing their susceptibility to fire. Should trees be killed by fire, an adequate source of viable seed is more likely to be available in the

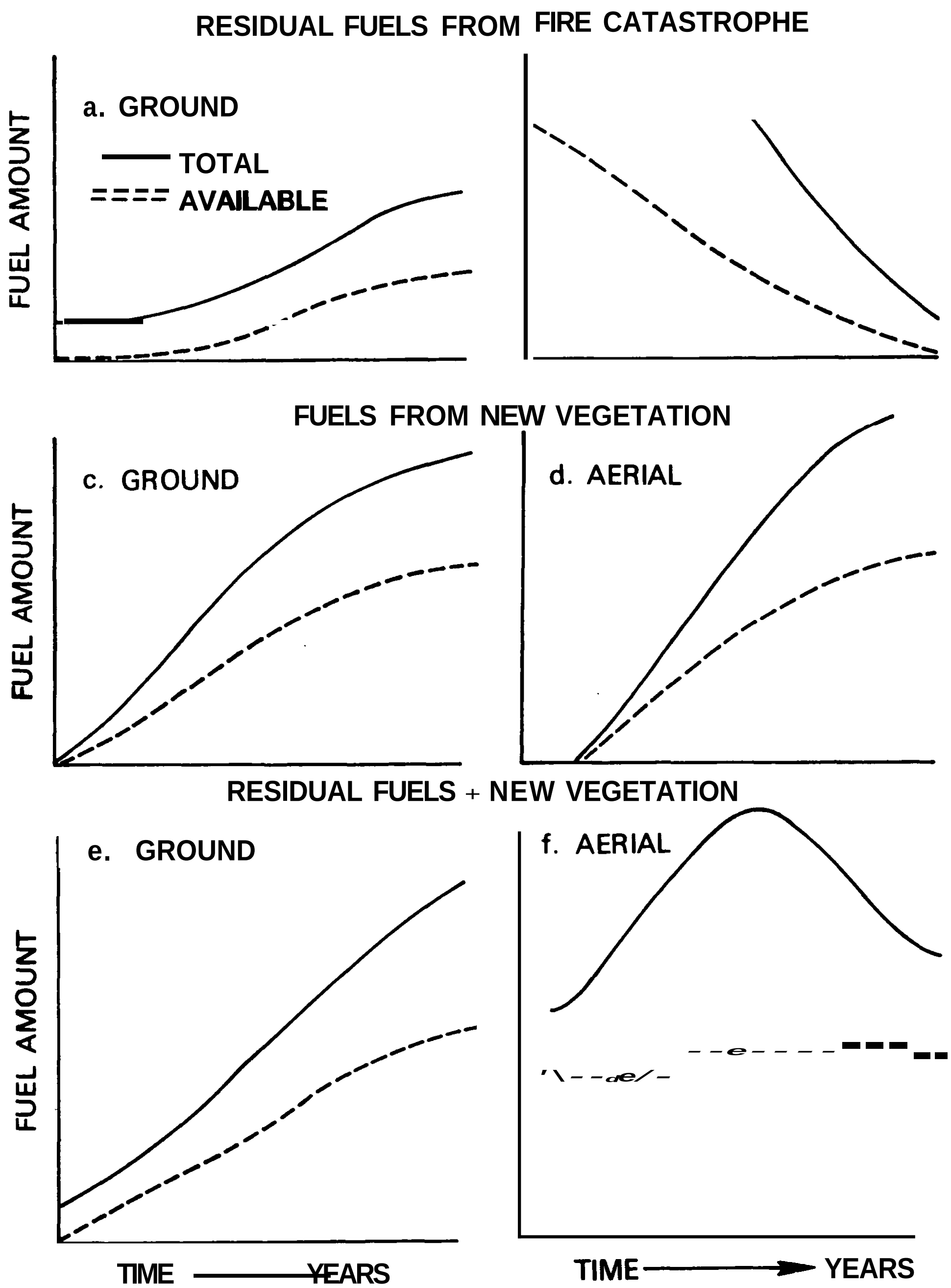

Figure 2.--Fuel variation in a timber stand over time after catastrophic killing of the stand. Available ground and available aerial fuels must always be less than or equal to total ground or total aerial fuels, respectively. Residual fuels (a and b) decrease over time. Fuels from new vegetation (c and d) include the entire aboveground portions of the plants and increase over time. The sum of the two fuel sources may vary depending on plant species, climate, and other factors. Time is indeterminate but full scale may be on the order of SO years.

crowns or from adjacent living trees. In species such as Douglas-fir or ponderosa pine, thick bark protects the stem from moderate ground fires. However, if fuels are allowed to accumulate, the heat generated by fire may be sufficient to kill or injure the stem as well as the crown.

Overmature or decadent stands change their characteristics gradually. There may be a transition into a more tolerant species, or a catastrophe may occur leading to regeneration of the stand. Here and there a tree is struck by lightning, leaving dead tops, branches, and barkless streaks down the bole. Falling trees damage others. Drought may cause dieback, leaving snag tops. Insects or disease invade damaged trees, causing additional damage or killing the trees. As trees weaken and eventually die, the hole left in the stand may be taken over by more tolerant conifers or hardwoods, shrubs, herbs, or grasses. These may add to the fuel complex and serve as a ladder from surface fuels to crowns. The dead trees or portions thereof fall to the ground, contributing fine and large fuels.

Fuel is available throughout the stand. Snag-topped stems may introduce additional sources of ignition from lightning. On the ground, large fuel components usually do not greatly affect rate of spread and may contribute little to energy release rates at the head of a fire. They may contribute to fire-induced mortality, however, through sustained heat generation, allowing greater penetration of lethal temperatures into stems and surface soil layers. Crowns may be heated and desiccated; seeds may lose viability.

Looking at the effects of one or more light ground fires in the mature to overmature forest (fig. 3), we can see the reduction in conflagration potential. These curves are drawn as though the life of the timber stand began with some residue from logging but not withstanding trees or snags. One might argue about the trend of the curves, depending on burning conditions, but some important considerations are given below. The ground fire consumes all the available ground fuel--that which would burn under the conditions of the fire. Total ground fuel is reduced by the same amount as available ground fuel. Generally, the light fire would remove the smaller or more loosely packed fuels, such as the upper litter layers, and a thin outer or upper layer from the larger fuel components and more tightly packed duff and humus. After the fire, the rapid buildup in ground fuel may be attributed to drying of lower duff and humus, death of shrubs, deposition from aerial fuels, and stimulation of herbaceous vegetation.

Since we specified the fire as a light ground fire, it would not consume aerial fuels. The heat of the fire affects availability of aerial fuels, however; it kills needles, branches, and main boles of some trees. Thus, the amount of aerial fuel available for a more severe fire may rise sharply but drop off rather quickly as the newly killed parts become available for burning and then fall to the ground, contributing to a rapid though temporary buildup in available ground fuel. Total aerial fuel would not change appreciably except to reflect the loss of needles, branches, and tree stems. If the prescribed fire is light, the remaining trees rapidly fill in any crown openings and quickly occupy the entire site.

Light prescribed fires have reduced conflagration potential in more than one way. Most significant is that the fires have reduced available ground fuel. In so doing, they have dampened the fuse that must supply the energy necessary for a conflagration. First, by removing the faster burning ground fuels, light

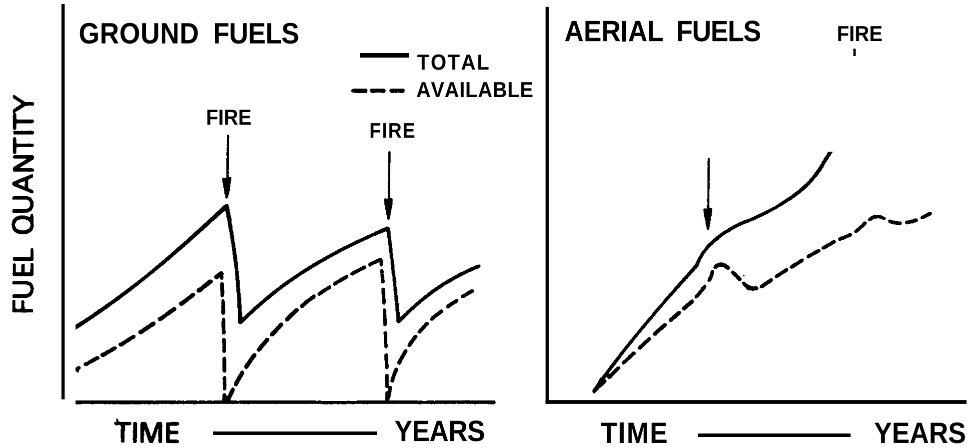

Figure 3.--Fuel reduction from periodic light fires underburning in mature or overmature timber stands. The temporary increase in available aerial fuels is due to death of lower needles, limbs, and some trees. Total aerial fuels may lag somewhat but then increase more rapidly as crown closure again becomes complete. Available ground fuel may climb more rapidly due to deposition of killed tree parts. Time is indeterminate but full scale may be as great as 50 years.

prescribed fires reduce the potential energy release rates. Second, without the high energy release rates from ground fuels, aerial fuels might not become available to a fire. Third, light fires tend to kill the lower branches and remove tall brush--the ladder fuels. Thus, over time, the aerial fuels grow higher, making it more difficult for fire to bridge the gap into the crowns.

Thus, light prescribed ground fires, where applicable, can effectively decrease conflagration potential in a living stand. Hotter fires, however, may produce more fuel and increase conflagration potential by killing the stand.

MAN-INFLUENCED FUEL COMPLEXES

Man-influenced fuel complexes are those where man is responsible for modifying the natural fuel complexes, usually by silvicultural activities associated with timber growing and harvesting. As with "natural" situations, we might begin with a young stand. Basically, there are few real differences between the "natural" and "man-influenced" fuel complexes. Differences may lie in the timing and suddenness of changes.

Beginning with regeneration, surface fuels may be about the same. If a dead overstory exists, man may fell these to help insure his investment in the new stand. Further, he may poison or cut overtopping hardwoods and spray competing brush. These would then add to the surface fuel complex, the timing depending on methods involved.

Stands entering the sapling or pole class may be too dense and must be thinned. Thinning may involve felling stems, poisoning, or use of fire, the latter two methods leaving stems standing. Felling the stems produces a more immediate severe fire hazard. Standing dead stems do not present so severe a hazard at one time but extend the period of high hazard. Either way, hazard is increased; but it can be reduced by prescribed fire.

Figure 4 shows the rapid increase in total and available ground fuels at the time of thinning. Removing some commercial stems affects total ground fuel somewhat but has little effect on available ground fuel or on short-term conflagration potential. Without fire or other means of reduction, total and available ground fuels will remain above ground fuel quantity in the unthinned stand for several years. Prescribed fire has much the same effect as a low intensity fire in unthinned stands. More total fuel remains, but overall conflagration potential is greatly reduced.

As the stand passes into the merchantable category, larger materials removed by thinning are utilized. The smaller the size of stem utilized, the more total fuel hazard is reduced and the easier it will be to maneuver in the stand.

Materials left include tops and branches. The amount of residue left by thinning can be enough to increase surface fuels from innocuous levels to a serious fire problem in both damage potential and fire control. Prescribed fire can be used, however, to reduce the hazard.

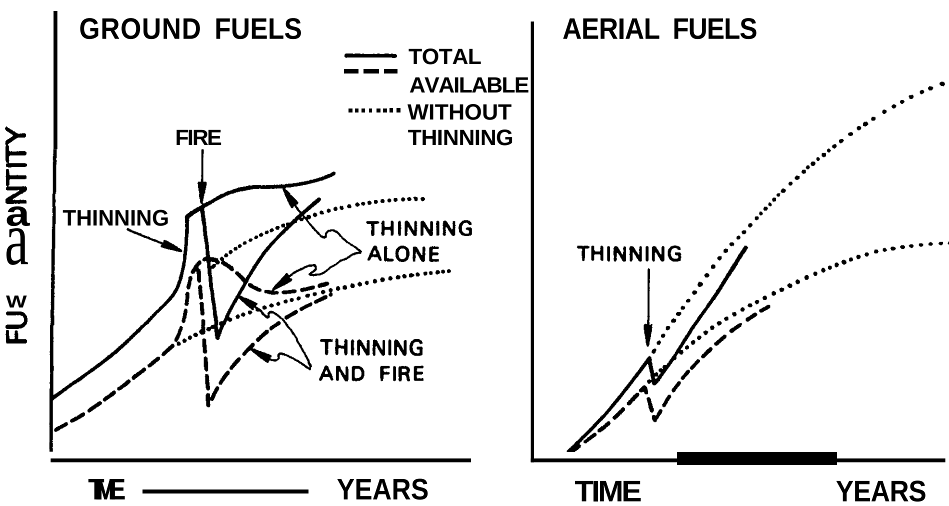

Figure 4.--Effects of thinning and burning on fuels. Thinning will decrease total and available aerial fuels for a time but will drastically increase ground fuels. A properly prescribed fire following thinning can reduce total and available ground fuels to a tolerable level. Time is indeterminate, but full scale is on the order of 50 years.

Cutting in mature stands usually results in even greater amounts of residue. Generally, the type of fuel, will be similar to that from thinnings, although more large material is generated. Common practice is to burn this slash.

Cutting in old-growth, overrnature stands often leaves large amounts of decayed and broken cull material on the site, as well as larger tops and branches. These produce an excessive amount of fuel and add greatly to fire control and regeneration difficulties. The large portions decompose slowly and produce punky fuels which can harbor holdover fires.

The clearcut operation removes aerial fuels while greatly increasing ground fuels (fig. 5). This is the fuel complex which has received the greatest attention in the Pacific Northwest. Although some companies have reduced the hazard by improving utilization, such practices remove more of the larger fuel components but still leave the smaller, more dangerous fuels. Nevertheless, closer utilization does decrease hazard, reduce difficulty of control, and leave less material for future problems.

Generally, much of the harvest residue is removed from the site. Slash burning is the most common method and the cheapest if done properly, and it removes the finer fuels with the higher energy release rates and rates of spread. If additional material is utilized--successively smaller sound wood pieces--and the slash reduced by fire, we could arrive at a point where little material remains.

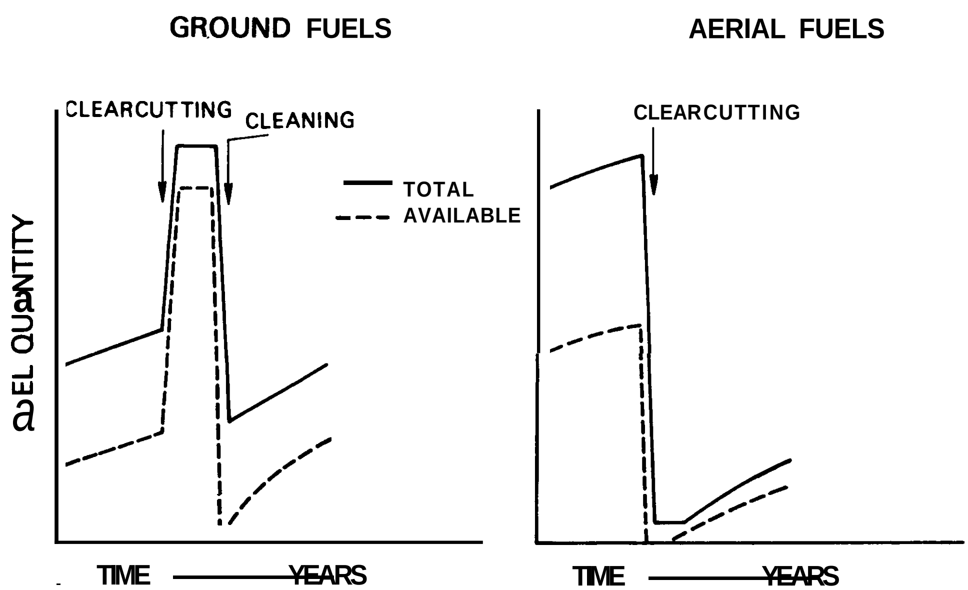

Figure 5.--Effects of clearcutting and cleaning operation--burning, hauling, burying--of fuels. Clearcutting removes essentially all aerial fuels (unutilized trees are felled) but greatly increases ground fuel. Any cleaning operation greatly reduces fuel level. Full scale on the time axis is of the order of 10 years.

Clearing for roads and other purposes often produces large piles or windrows of heavy fuels including stumps. This material contains rocks and soil, making mechanical reduction difficult. When heavy accumulations are along roads, the risk of fire from man is increased, adding to control problems.

The amount and flammability of Northwest slash fuels have been studied. Olson and Fahnestock (1955) reported on slash fuels in the Inland Empire area. When the same amount of footage from second- or old-prowth stands is cut, over twice the volume of space is occupied by the slash produced from the younger stand. They demonstrated that volume of space occupied by slash from a tree is reduced about 40 percent by lopping, 93 percent by piling, and 98 percent by chipping. They also discuss the overall slash problem and management alternatives. Fahnestock and Dieterich (1962), in a continuation of the above work in the Northern Rocky Mountains, reached several conclusions concerning slash flammability: Slash is hazardous in proportion to the quantity and durability of fine components, to the length of time it is dry each year, and to the degree fine material is elevated above the ground. Heavy concentrations of slash from western white pine (*Pinus monticola* Dougl.), lodgepole pine, ponderosa pine, and western hemlock, and sometimes Douglas-fir and Engelmann spruce (*Picea engelmannii* Parry) warrant a high rate of spread even after 5 years. Grand fir (*Abies grandis* (Dougl.) Lindl.) and western larch (*Larix occidentalis* Nutt.) rapidly lose their high flammability due to disintegration of the fir and the sparseness, loss of needles, and low profile of the larch.

Various sampling methods have been used for determining the amount of fuel present. For estimating the amount of logging slash, an adaptation of the line intercept method developed by Warren and Olsen (1964) and modified by Van Wagner (1968) appears to be the most satisfactory for measuring materials down to a 3-inch (7.6-cm) diameter (Howard and Ward 1972, Dell and Ward 1971). Brown (1971) further refined the line intercept method so volume or weight of residue less than 3-inch diameter could be estimated. The subjcct of inventory of downed woody material is more thoroughly covered by Brown.[4/] Muraro (1970) used low-level aerial photographs for estimation of slash in the Northwest with reliable results.

The tremendous amounts of residues developed from logging operations are either treated or given a high level of fire protection for several years. Since almost half the slash in the Pacific Northwest is chippable, our present level of utilization seems to leave considerable room for improvement. At the same time, the large amount of slash increases the problem of slash disposal or of fighting fire in the unit. The larger, more persistent materials will make use or control of fire in new stands more difficult for many years to come.

FUEL MANAGEMENT

In this paper we have concentrated on forest residues and living vegetation as fuels. We have discussed both the kinds and arrangements of natural fuels and the rearranged fuels from cultural and harvesting operations. Rarely do these fuels just happen to be in harmony with the forest environment or

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[4/] James K. Brown. Handbook for inventory of down and woody material in western forests. (In preparation for publication, Intermountain Forest and Range Experiment Station, Ogden, Utah.)

management objectives. Both natural and harvest-related fuels are likely to require treatment, and this is best not left either to chance or until a crisis situation develops that demands treatment. Careful setting of objectives and planning to achieve them is necessary, i.e., purposeful fuel management.

But there is considerably more to the management of forest residues than fuel management--there are considerations of wildlife habitat, nutrient cycling, esthetic impact, soil health, etc. These other aspects of residue management are covered in other chapters of this Compendium. Though fuel treatment aspects of residue management have, up to the present, received the greatest attention, residue management now must accommodate the needs of all the components of the forest environment it affects. Although recognizing these much broader considerations of forest residue management, we confine our attention here primarily to considerations of forest residues as fuels and to fuel management.

For balanced forest management, the concepts and practice of fuel management must penetrate and become a conscious part of all phases of forest management planning and operation. Forest management is still fundamentally a program for managing vegetation to achieve objectives, but this needs to be done with a deep concern for fire. The effort that is put into fuel management in the preharvest decisions and preharvest operations is probably more important than any stopgap treatment that can be applied after harvesting.

In fuel management as in other aspects of forest management, large areas such as cutting circles as well as individual cutting areas should be considered. We can, for example, harvest timber from a small area and be concerned about the management of fuels on that unit. But unless we consider those fuels as only a part of a larger pattern of adjacent vegetative or timber types and fuel situations, we may make poor fuel management decisions. By looking at the total patterns of fuels, forests, and uses, we can plan distribution, size, and shapes of harvest areas and kinds of treatment to achieve the most efffective pattern of high and low hazards.

Vegetative types do not have consistently high hazards throughout their life history. There are times when most stands will hardly burn. There are other times when they are very susceptible to fire. Man's primary influence on vegetation is through changing the composition, quantity, arrangement, and timing of stages of development. Judicious planning of cultural treatments such as thinning, pruning, light underburning, and harvesting can produce useful discontinuities in the fuel and optimum patterns for separation of units in high hazard stages. Similar considerations apply to the fuel type distribution in the unmanaged forest where previous fires, changes in topography, or climatic differences have produced discontinuities in fuel.

Appropriate treatments need to be planned in advance to assure attainment of both silvicultural and fuel management objectives. The desired arrangement, amount, and continuity of fuel can be designated. Logging areas can be designed, the method of harvesting and the utilization standards can be specified, and the preparation necessary for fuel treatment can be spelled out. Fuel aspects of efficient, effective residue management demand that planning for fuel treatment go hand in hand with planning for silvicultural treatment. Only in this way can we avoid continually winding up with a fuel situation that has to be corrected.

Where continuous masses of fuels from man's activities or from natural disasters are already present, fuel treatment is likely to be necessary. Development of a meaningful pattern of fuel discontinuities, of which fuel breaks are one type, should have first priority. This would permit easier access and toehold locations for fire control operations. The discontinuities will also interrupt the fire cycle so that the fire has less opportunity to build up to conflagration proportions. Constructed or existing natural fuel breaks or less flammable vegetative types might make treatment of the entire area unnecessary. For logging slash, a simpler solution might be to require cleanup during and immediately after logging by (1) tighter utilization requirements and (2) immediate treatment of the remaining residue, both planned in advance of logging. But with the fuels already present, the remaining alternatives are: (1) change the nature of the fuel, (2) change its distribution, or (3) remove it. The alternatives for treatment decisions after logging are more limited than those that exist before harvesting; but unless both harvesting and slash treatment are planned beforehand, we may create new problems faster than we are able to correct old ones.

Effective breaks or voids in continuous fuel beds may be created by mechanically removing the fuels. However, if the objective is to reduce the fire intensity, then appropriate amounts of various size materials can be removed to achieve the desired effect. If fuel loading is extremely heavy, some removal should be considered even though compaction and crushing reduce rates of spread. Without removal, fire intensities may still be so high as to create strong convective winds that will produce many embers and spot fires. An oversimplified rule-of-thumb says that for a given loading of fuel, a reduction in fuel depth by half can cut the expected rate of spread in half.

Limitations of methods available for fuel reduction must be considered. Certainly, much equipment cannot be used on steep slopes. For soils that are particularly vulnerable to compaction and accelerated erosion, time of year for treatment is important. Therefore, the prescription for fuel treatment ought to be designated only after the potential for machine use has been estimated. Residue treatment methods, such as burying in a pit, that involve severe soil disturbance several feet in depth should be questioned. The building of healthy, dynamic soil profiles requires many years. Permanent damage to soil is a questionable price to pay for temporary hazard reduction and may make the cure worse than the problem.

Possibly some new approaches need to be examined, such as removal of material by helicopter or balloon. These methods would, of course, be used only when economic, operational, and environmental considerations showed them to be a clear advantage. Other methods are limited by the smoke produced (Cramer 1974) or the resulting impact on scenery (Wagar 1974). For some situations, essentially smokeless open incinerators may be the answer. Each method has its limitations as well as its capabilities.

Decision and planning aids for forest residue management are getting long-needed attention. Some agencies, including the Pacific Northwest Region of the U.S. Forest Service, are developing checklists of items to be considered in planning fuel management: type of vegetation on the area, quantities of fuel that will be generated, proximity to water sources, problems of smoke management from burning treatments, and so forth. The Pacific Northwest Forest and Range Experiment Station, in cooperation with Region 6, State, and private forest managers and scientists, is now developing guidelines for residue management based on present knowledge of environmental needs and effects. These guidelines, specifying the condition in which the forest is to be left for various forest and use situations, will greatly aid the definition of fuel management objectives to be achieved through forest management operations. Other knowledge is being developed as are methods for making existing knowledge more readily available to planners of residue management.

RECAPITULATION

An effective program of forest fuels management is our most promising long-range fire management tool. Fuels accumulate in our forests but are often disturbed by man. Reduction of the accumulations historically has been through fire--sometimes gentle and frequent where accumulations were low, conflagrations where accumulations of fuel were heavy. We have attempted, in the past, to prevent conflagrations by building efficient and effective fire control organizations. Effectiveness of these organizations is evident from fuel accumulation, so that we presently have powerful fires that overwhelm our firefighting organizations. Since manipulation of weather or climate is beyond man's present capability, our greatest opportunity for fire management and conflagration prevention must be through fuel management. By managing forest fuels, we work within the natural system'in our forests rather than attempting to buck it through the brute strength of fire control organizations. Fire is a natural component of the forest system. Use of prescribed fire may accomplish many silvicultural, ecological, esthetic, or sociological purposes better than either a wildfire, in its sporadic way, or manual-machine manipulation. Properly used, fire removes the smaller fuel components. Improved utilization will remove larger components. Utilization, fire, and other treatments all have a place in reducing residue fuels.

There are two main avenues through which we might alleviate our residue-fuel problems:

1. Fire considerations (as well as other environmental effects of forest residue) must be taken into account with the initial considerations for management of a forest area.

    (a) Models are being developed for management decisions involving realistic evaluations of fire potentials.

    (b) Appropriate actions can be taken to reduce fuel loadings in patterns designed to reduce potential wildfire spread and damage.

    (c) Personnel qualified to evaluate objectively fire potential and develop plans for fuels management can be employed.

2. Improved utilization practices must be used. Management plans should be modified to require maximum removal of material.

CURRENT RESEARCH IN FOREST FUELS

The following list (A) of research groups represents only the primary programs in which forest fuels receive major attention. Since this field changes rapidly, a second list (B) is of contact points where information on current research is available.

A. Major programs of research on forest residue as fuel:

Northern' Forest Fire Laboratory, USDA Forest Service, Missoula, Montana--research programs in fuel science and other aspects of fire.

Southern Forest Fire Laboratory, USDA Forest Service, Macon, Georgia--research programs in fuel management, smoke management, and forest fuel combustion emissions.

Forest Fire Laboratory, USDA Forest Service, Riverside, California--research programs in fuel breaks.

North Central Forest and Range Experiment Station, USDA Forest Service, Fire Control Project, East Lansing, Michigan.

Pacific Northwest Forest and Range Experiment Station, USDA Forest Service, Portland, Oregon--(1) Forest Residues Reduction Research, Development, and Application Program; (2) Cooperative Forest Fire Management and Science Program, University of Washington, Seattle.

B. Contacts for current details on forest fuel and residue research:

Assistant Director, Division of Cooperative Fire Control, State and Private Forestry, Washington, D.C. , stationed at Berkeley, California.

Assistant Director, Division of Cooperative Fire Control, State and Private Forestry, Washington, D.C., stationed at Missoula, Montana.

NEEDED RESEARCH

I. There is serious need for decision models that for any forest situation will indicate the combinations of management actions that will produce an optimum balance of fuel management considerations with economic, social, political, ecological, esthetic, and administrative values. Planning and operational functions are both hampered by imprecise methods of evaluating alternatives. Such decision models will require, among other things, development of:

A. An objective means of appraising fuel situations and fuel modifications in terms of fire potential.

B. A more realistic three-dimensional fire model to replace the present two-dimensional model.

C. Methods for model simulation of complex fire situations including identification of the threshold points of blowup fires and conflagrations.

D. Methods to more adequately measure and describe the influences of wild and prescribed forest fire on the atmosphere, soil, water, flora, and fauna, as well as on economic and social values.

11. We need knowledge of the effect patterns of fuel distribution have on the fire hazard in a cutting unit, and the pattern of units with varying degrees of hazard is important to the broader scale pattern of conflagration potential. Yet the influence of fuel distribution patterns on hazard is not well understood. Further research is needed so that effective fuel arrangement and the treatments to achieve it can be specified as a part of preharvest planning. Components of this problem needing study include:

A. How much of the area needs to be treated?

6. How large an area of hazard can we permit within an area of lower hazard?

C. What patterns of fuel treatment can bring the hazard of a management area to a reasonable level?

III. Achievement of an intensity of residue management in keeping with other aspects of quality forest management is needed. This depends on:

A. Refinement of techniques for minimizing production of residue during forest harvest.

B. Improved methods for economical handling of larger residue so that utilization may play a greater part in residue management.

C. Development of techniques and prescriptions for more precise use of fire for residue treatments over a greater range of residue situations.

D. A decision aid for selection of the method of residue treatment best suited to any given combination of management objectives, forest environment, and residue situation.

IV. A better understanding of the evolution of forest residue complexes with time is an essential need for long-term planning of residue management.

A. It is necessary not only to establish the correlation between existing fuel hazard and specific plant communities but also to predict successional changes in the plant communities and, more important, the attendant successional changes in the fuels.

B. The long-term impacts of current fuel treatments need to be determined. Removal of only fine or medium fuel may be of immediate value, but what will be the fuel: condition in 20-50 years when the large fuels decompose? Many fires escape control or become large because of multiple ignitions in punky fuel that may have been decomposing on the forest floor for many years.

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RECREATIONAL AND ESTHETIC CONSIDERATIONS

J. Alan Wagar

ABSTRACT

Reviews studies of landscape quality and draws together interim guidelines for reducing the recreational and esthetic impacts of forest debris. Guidelines are in three groups: broad management planning (emphasizing zoning; lengthened rotations; partial harvesting; and the physical size, shape, and arrangement of cuttings), manipulation of forest debris (emphasizing "naturalness" where possible, otherwise emphasizing "orderliness"), and management of forest visitors (guiding them to the most pleasant stages of rotations and helping them understand what they see).

Keywords: Scenic beauty--forest recreation, landscape planning, perception.

INTRODUCTION

As demonstrated by a great amount of controversy, legal action, and legislation, public concern with recreation, esthetics, and the environmental quality has increased greatly in recent years. The effects of timber management are an important part of this concern. Harvesting operations are continually penetrating areas previously free from roads and logging. At the same time, rising affluence, leisure, and mobility have permitted more and more people to visit the forests for recreation, scenery, and other environmental amenities.. In fact, it is primarily in such pursuits that people now come into contact with forests and forest management.

The urbanites who now predominate among forest visitors generally do not think of forests as places for jobs and the sustained production of essential commodities. This does not mean, however, that material demands have decreased. Instead, demands for such forest commodities as lumber, plywood, and paper have grown along with demands for recreation and environmental amenity.

In contrast with the "land surplus" conditions that minimized forest management conflicts until fairly recently, it is now difficult to make any management decision on our finite forests without damaging someone's interests. It is within this context of competing values and increasingly difficult choices that the recreational and esthetic effects of forest debris must be considered.

DEBRIS VERSUS AMENITY

Although such events as wildfire, epidemics, and violent storms may on occasion create massive amounts of forest debris, logging slash is by far the most prevalent debris problem affecting forest amenity. (The term "amenity" is used here to include both recreation and esthetics.) Being man-caused, slash and the debris from thinning and pruning are the most readily subject to management and the most in violation of the widespread preference for naturalness in forest landscapes.

This preference for naturalness has been found in many studies (Yarrow 1966, Twiss and Litton 1966, Lime and Cushwa 1969, Peterson and Neumann 1969) and suggests that some visitors will overlook, expect, or even wish to encounter debris from natural or natural appearing causes.1/ Nevertheless, natural debris may, in some cases, be as damaging to recreation and scenery as the residues of timber harvesting.

Although only a few studies have considered forest debris in relation to recreation and esthetics (Wyoming Study Team 1971),2/ 3/ much has been written about esthetics, perception, and landscape quality. By examining the general processes of perception, and especially how people perceive and evaluate landscapes, we can infer much about recreational and esthetic considerations in the management of forest debris.

A starting point is to recognize that perceiving is not equivalent to seeing. As Saarinen (1969) points out, perception depends "on more than the stimulus present and the capabilities of the sense organs. It also varies with the individual's past history and present 'set' or attitude acting through values, needs, memories, moods, social circumstances, and expectations." Thus, what one viewer perceives as desirable land management, another may perceive as esthetic degradation or even permanent devastation. For example, in a study by Boster and Daniel (see footnote 3), the Arizona Water Resources Committee and a sample of university students rated the scenic value of several treatments of ponderosa pine quite differently. The students rated treatments of "irregular strip cut," "heavy thin," and "clearcut" as progressively less attractive than an uncut stand. In contrast, the Water Resources Committee rated these three treatments as more attractive than the uncut stand.

SLASH AS AN AMENITY MISFIT

From an esthetic and recreational point of view, disposal of slash and other forest debris usually requires making the best of a negative situation--especially in large old-growth stands. Alexander's (1964) detailed discussion of acceptable

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1/ Kenneth H. Craik. Forest landscape perception: final report to Forest Service. Contract No. A5fs-16565, 40 p., 1969.

2/ Ernest M. Gould, Jr. Forest planning for amenity and timber production. Report to Forest Service on Grant Research Project #1, FS-WO-1902, 167 p., 1968.

3/ Ron S. Boster and Terry C. Daniel. Measuring public responses to vegetative management. Paper presented to the 16th Annual Arizona Watershed Symposium, Phoenix, 16 p., Sept. 20, 1972.

form provides two principles that help greatly to explain why logging slash is so widely perceived in negative terms. The first concerns the relation between form and context. The second concerns the relative ease of defining what is not fitting compared with what is fitting.

Alexander related form and context as follows:

> The form is a part of the world over which we have control, and which we decide to shape while leaving the rest of the world as it is. The context is that part of the world which puts demands on this form; anything in the world that makes demands of the form is context. Fitness is a relation of mutual acceptability between these two.

In Alexander's terminology, amenity problems from logging slash result from relatively unchanged form (unsightly debris) and greatly changed context (public mobility and expectation). Coupled with the public's increased mobility and environmental concern, its widespread preference for "naturalness" provides a changed context "that makes demands of the form" which are unlikely to be met unless the form itself is changed.

The fitness of form to the contextmay involve many variables, including such things as shape, color, texture, scale, and the experience and expectations of the viewer. But a "misfit" need involve only one variable. As a result it is much easier to define misfit than what is fitting.

A number of studies have substantiated this principle. Rabinowitz and Coughlin (1970) found that "dislike" of landscapes "...seems to focus on individual elements, and primarily man-made ones." They defined "misfit" as "any man-made object not significant or obviously attractive," (Rabinowitz and Coughlin 1971). In discussing classification of scenery, Sargent (1967) found the term "eyesore" useful.

An illustration of the esthetic judgments likely to be associated with slash was supplied by Craik's (1972) use of the Landscape Adjective Check List (LACL). In a test of the LACL, Craik asked a panel of 21 students in landscape architecture to rate landscape photographs previously rated as having high, low, and intermediate esthetic appeal by a panel of 60 geography students. All photos displayed "minimal signs of human activity." Using statistical tests, Craik found the following adjectives to be significantly associated with esthetically unappealing scenes:

arid	destroyed	scraggly
bare	dirty	ugly
barren	drab	unfriendly
bleak	dry	uninspiring
brown	dull	uninviting
burned	eroded	weedy
bushy	golden	windswept
colorless	hot	withered
depressing	lifeless	worn
deserted	monotonous	yellow
desolate	plain	

The magnitude of esthetic problems caused by slash is indicated by the number of adjectives above that fit the scene found after logging and especially after clearcutting. In contrast, the list of 57 adjectives significantly associated with esthetically appealing scenes included:

alive	fresh	pure	wild
clean	green	secluded	wooded
clear	living	timbered	
cool	moist	unspoiled	
forested	natural	vegetated	

Such studies suggest a series of dimensions that underlie people's judgments of landscape quality.

DIMENSIONS OF LANDSCAPE AMENITY

Studies of landscape quality fall generally into three categories: physical descriptions, judgments of quality, and analyses of the psychological dimensions involved in landscape preferences.

Litton's work (1968, 1972) is a good example of objective description for landscape inventory, and Craik (1972) has found substantial agreement among different observers asked to apply Litton's landscape rating scales. Although the scale categories identify landscape configurations to which experts might ascribe different quality, application of the categories themselves does not require esthetic judgments.

A second category of efforts includes systems for judging the value or quality of landscapes. Some of these, like Crowe's (1966) "Forestry in the Landscape," are explicitly presented as expert opinion growing out of long experience and professional judgment. Other studies, however, such as those of Sargent (1967) and Leopold (1969), attempt to increase consistency and "objectivity" by developing numerical scores for various attributes of the landscape. Such numerical scoring is useful for training diverse observers to apply uniform criteria for classification. But value judgments are invariably built into the weights assigned to different elements of a composite score, making the scoring systems no more objective than the value judgments of their authors.

A third category of studies explores the psychological dimensions which seem to underlie people's judgments of what they see. Some of these draw primarily upon literature and professional opinion (Twiss and Litton 1966, Lynch 1960).4/ Others add the results of interviews, surveys, or experiments to test people's reactions to diverse scenes (Shafer et al. 1969, Gratzer and McDowell 1971, Craik 1972; see also footnotes 2 and 3).

Several dimensions of landscape amenity can be drawn from the three categories listed above. Those that seem pertinent to forest debris problems are naturalness, imageability, legibility (or meaning), texture, topographic relief, harmony of shapes, scale, passibility, horizontal order, vertical order, plant form, and waste.

4/ See also Robert H. Twiss. Regional landscape design: An approach to research and education. Paper presented to the National Council of Instructors in Landscape Architecture, Harvard Univ. 10 p., 1965.

Naturalness. Although a widespread preference for "naturalness" has been found repeatedly among people judging landscapes, Rabinowitz and Coughlin (1970) found in a Pennsylvania study that what people *perceive* as natural is clearly landscaped. They found a marked preference for "parklike" scenes and noted that "Mowed grass and scattered large shade trees seemed to be the determining factors."

Imageability, as defined by Lynch (1960), is "that quality in a physical object which gives it a high probability of evoking a strong image in any given observer." Lynch was referring to mental images. In discussing imageability, Twiss and Litton (1966) noted that "observers tend to notice things which already have strong or symbolic meaning for them. Many will be shocked by the sight of bulldozers, slash piles, and tree stumps; but they may be reassured...if it is obvious that the land is being used with care."

The importance of symbols and symbolic meanings must not be overlooked. In our highly complex society, most of us must form our opinions on most issues on the basis. of symbols rather than the complex networks of causes and consequences that are only partly understood even by the experts. Thus, in the oversimplifications of public opinion, the scene at a recently logged area can become either a symbol of good stewardship or a symbol of rape. Also, as competition increases among forest land uses, we can expect proponents of specific views to give logging debris symbolic meanings designed to sway public opinion toward similar views.

Legibility (or *meaning).* In discussing the cityscape, Lynch defined legibility as "the ease with which its parts can be recognized and can be organized into a coherent pattern." Identifying pattern and meaning is also vitally important for landscapes, especially forest landscapes that are being manipulated in ways that are easily misunderstood by nonspecialists. In fact, if timber harvesting patterns are arranged so that sustained productivity and good stewardship are easy to see and understand, observers may see that. many fears and criticisms are unfounded.

In contrast with professional land managers, most members of the public do not have specialized knowledge of regeneration, working circles, rotations, sustained yield, etc. As a result, their opinions of management must be based largely on visual clues. The visual clarity of good forestry seems to depend greatly on visual unity which Litton (1972) defined as "that quality of wholeness in which all parts cohere, not merely as an assembly but as a single harmonious unit."

European forests provide many examples of highly legible or meaningful landscapes in which sustained cropping of trees is self-evident. For a variety of reasons, cutting areas in European forests are usually small, seldom larger than 10 or 15 acres. As a result, even where clearcutting is practiced, each view of the forest landscape tends to include stands of many age classes, often intermixed with agricultural crops in a highly humanized landscape that has a look of permanent equilibrium. This seems to permit the dynamics of sustained production to be readily seen and understood as a unified whole, permitting viewers to see forest management, including slash or slash treatment, as a part of a continuous process.

In contrast, where clearcutting is practiced in the United States, both cutting areas and working circles are often so large that individual views are dominated by a few stages in the rotation rather than by an orderly sequence of many stages. It may, therefore, be desirable to divide each working circle into a number of small "visual management areas" in which small cuttings are timed and spaced so that the whole process of sustained production is readily seen from a single viewing point. This would make it easy to identify slash as a small and temporary portion of the total cycle.

Texture. Psychologists point out that we normally perceive a shape or "figure" as contrasting with its surroundings or "ground" (Bouman 1968). Texture plays an important part in this figure-ground phenomenon. In a continuous textured forest, such as Douglas-fir ***(Pseudotsuga menziesii)*** west of the Cascades, any small opening tends to stand out as "figure" against the continuous "ground." However, in forests such as open stands of ponderosa pine ***(Pinus** ponderosa)* that have many small openings, additional openings remain as part of a coarse-textured "ground" and do not become "figure." In many European landscapes, the texture is even coarser so that fields, pastures, timber stands, and even villages may all become a part of "ground," permitting timber harvesting with little disturbance to visual quality.

Just as tweed does not show stains as readily as gabardine, management of coarse-textured landscapes should create less visual degradation than similar management of fine-textured landscapes. This suggests that some of our most productive forest sites might best be converted to coarse-textured visual management units.

Topographic relief. In mountainous areas, where differences in elevation are great, any timber management activities will usually be highly visible. In addition, the most mountainous areas tend to be in public ownership and thus subject to the conflicting demands of amenity and commodity production.

***Harmony of** shapes.* The shape of cuttings is important, in addition to their size and the stage of regrowth. As Crowe (1966) observed, some of the worst patterns result from straight lines "cutting across contoured ground." If straight lines are used, they should "run diagonally over the contours." Shapes can often be harmonized with landforms by "following the tilt" of rock strata, by leaving tree cover in saddles, and by leaving clumps of trees either within clearings or as outliers.

The edges between contrasting parts of the landscape define shapes and are especially important. By using photographs of landscapes and an eye movement recorder, Gratzer and McDowell (1971) found that the "most common area of (visual) concentration were along 'edges' and on small objects (less than a 1° arc)." Edges included skylines, ridge lines, shorelines, vegetation lines, and shadow lines. Depending on how they fit into the total scene, edges can be perceived as inappropriate discontinuities or as "seams" that join together harmonious elements (Lynch 1960).

Edges that suggest disharmony should be softened. In timber harvesting, this might be done by making openings small, irregular, and similar to natural shapes already present; by orienting openings for minimal visibility from the most likely viewing points; by using shelterwood harvesting throughout a cutting or around it to provide a "feathered edge" (USDA Forest Service [n.d.]). Feathering might also be accomplished by cutting the boundary several years ahead of time, thus providing advanced reproduction as a transition between the clearing and forest.

Scale is important both for maintaining harmonious balance in the total landscape and for subordinating unpleasant elements. Crowe (1966), for example, indicated that large blocks of timber and open areas may fit well on "large-scale, rolling hills" and badly on "small-scale and delicately modelled hills." Scale can also be used to subordinate unattractive elements of a scene. For areas of slash, this may mean leaving a residual stand or clumps of large trees that dwarf the debris on the ground, especially if the size of the debris is reduced by lopping and scattering, burning, chipping, or crushing.

Passability (degree of obstruction) is an especially important dimension of landscapes used for active recreation. Large accumulations of debris from harvesting, fire, windthrow, epidemics, or other causes may be impassable as well as unattractive. As indicated by Gould (see footnote 2), the alternatives and remedies include "Wait for debris to rot; speed rotting by lopping and scattering, chip or burn slash; salvage trees; cut paths; partial harvest to reduce debris; lengthen rotation for less frequent misfits."

Horizontal order, as defined by Gould (see footnote 2), is "the dominant pattern set by trees and dead woody material on the forest floor." He suggested that a "horizontal order misfit" is present "if material is disorderly, over 1 to 2 feet deep, and covers more than about 50 percent of the area." Except for adding "hasten regeneration to obscure debris," Gould gives the same remedies as for passability misfits.

Vertical order. Gould (see footnote 2) suggested that "enough trees leaning in a jack-straw, chaotic manner out of context with upright stems can be unpleasant" and cause a "vertical order misfit." The remedies he suggested are "salvage of timber; felling and limbing snags; clearing vistas."

Plant form. Misfits in plant form, as discussed by Gould (see footnote 2), may occur "when scraggly, damaged, or forest-grown trees are left in the open," or when dead trees are left standing "following fire, epidemics, flooding, etc." Suggested remedies include "wait for small tops to enlarge and regeneration to cover lower boles; salvage trees; fell snags; selectively clear vistas and/or paths; lengthen rotation for less frequent misfits; partial cutting and salvage."

Waste. Because the casual observer has little basis for recognizing defective logs or logs which can't "pay their way out of the woods," he perceives much slash as wasteful and inefficient use of our natural resources. This suggests not only yarding of unmerchantable material (YUM) but changed scaling practices or other measures to increase utilization.

OBSERVER CHARACTERISTICS

Judgments of landscape quality depend on the characteristics of the observer as well as the characteristics of the landscape. Different observers not only will perceive the same scene differently but also will place differing values on scenes perceived in similar terms. As a result, all the landscape dimensions discussed above permit diverse and often conflicting judgments of value and acceptability. Both belief systems and roles are important in these judgments.

Belief systems.--What people believe about forest management depends on what they hear and see. What they hear is largely beyond the control of forest managers. School systems, news media, and conservation organizations all have far more power to communicate with the public than do forest managers. In addition, our society often teaches its members a deep distrust of logging. For example, every effort to open New York's Adirondack Forest Preserve to forest management has been struck down by the State's voters. Such attitudes seem to persist from the cut-out-and-get-out logging of the Northeast and Lake States.

Although what people see in the forests is more under the control of forest managers than what people hear about the forests, ambiguous scenes are likely to be interpreted according to people's beliefs. As a result of growing environmental concern, many people now seem anxious to make accusations and identify scapegoats for the "environmental crime" they hear so much about. Under such circumstances unsightly logging slash, although quite temporary, is readily perceived as environmental destruction. Also, public mobility and expectations have changed so rapidly that forest managers are now criticized for the visual effects remaining from management actions that were generally accepted at the time they were made.

Roles.--Even within a single pattern of beliefs, an individual's expectations of a scene may change substantially as he assumes different roles (see footnote 1). The same individual, for example, might at different times take up such varied roles as "driver on the way to work," "hunter," "camper," "seeker of scenery," or "wilderness traveler." Because most forest visitors now encounter forest debris while in some recreational role, their expectations and thus their perceptions may very well vary within a quite limited range.

RESEARCH FOR BETTER ANSWERS

The amenity problems caused by forest debris must be considered when alternative disposal or treatment procedures are examined. However, the crucial aspects of amenity problems involve environmental perception and policy decisions. Environmental perception research can identify the values different people assign to landscapes and the ways these values are changed by (1) various landscape treatments and (2) by the underlying standards which people use in assigning values. Policy decisions, although based on people's values and preferences, will necessarily require choices between conflicting sets of values which involve different costs. Therefore, in addition to studies of debris treatment methods and environmental perception, research is needed to develop improved procedures for making choices.

Treatment *methods*.--Alternatives for treating forest.debris might best be studied in terms of equipment, costs, fire hazard, ,and biological consequences. Amenity considerations are unlikely to require new kinds of treatment or modified treatment. Exceptions may include research on stains to change the color of debris and perhaps cost data for unusually complete treatments. The main thrust of research on the amenity effects of debris must be focused on how debris is perceived and procedures for weighing alternatives.

Environmental perception research.—Much environmental perception research is already taking place to identify the visual elements to which people respond in various settings. To overcome the difficult logistics of transporting observers to a variety of settings, observers rate photographs in much of this research (Shafer et al. 1969; Shafer and Mietz 1970; Coughlin and Goldstein 1970; Rabinowitz and Coughlin 1970, 1971; Gratzer and McDowell 1971; Kaplan and Wendt 1972; see also footnotes 1 and 3). Some of the studies then test the validity of ratings based on photographs by having observers rate the sites at which photos were taken (Coughlin and Goldstein 1970, Rabinowitz and Coughlin 1971; see **also** footnote **3).**

A variety of research strategies will be needed to identify the visual elements that are most important in determining how people perceive a scene. Two approaches that appear especially promising are the Landscape Adjective Check List (LACL) already mentioned (Craik 1972) and "Signal Detection Theory" (SDT) as described by Boster and Daniel (see footnote **3).**

When the LACL is used, the people who are sampled simply check, on a list of adjectives, all those that seem to apply to a scene. Analyses can then be made to identify dimensions consistent with patterns of choices.

In their use of SDT, Boster and Daniel (see footnote **3)** were seeking methodology that would be inexpensive, objective, and valid. To eliminate bias on the part of the experimenters, they used photographs taken in random directions from random points and then presented them to observers in random order. They also developed procedures to correct for the fact that different people might be using different standards as a basis for judgment. For example, one observer might be rating a scene for its potential as a scenic area while another is rating it only as a pleasant bit of countryside.

Perception depends greatly on what people know and believe. Therefore, studies are needed to determine how perception of landscapes and forest debris changes as people are supplied with explanations of what they are seeing.

Relative importance of commodities and amenity.--Although it is important to identify the dimensions of landscape amenity, especially for landscapes that involve forest debris, the crucial problem is to identify relative importance among conflicting demands upon the landscape. Acceptable landscape quality is inevitably a value judgment that must be made by the people involved. As Boster and Daniel (see footnote **3)** pointed out, "Any technique that purports to measure landscape quality must invite meaningful public participation."

Meaningful public participation, as one part of defining appropriate quality for forest landscapes, implies much more than collecting and classifying opinions about beauty. The crucial questions are: What constraints on commodity production are created by various standards of amenity? How can the choices or trade offs between commodities or amenity be presented to people in understandable terms? What can be done to improve the range of available choices? And, given available choices, what constraints on commodity production are justified by amenity?

The most effective direction for research will depend primarily on the "style" of public forest management. If the goals of management are defined primarily within agencies, then a continuing series of studies will be needed to define what people seem to want or seem willing to accept. Although research might identify rather stable dimensions of landscape amenity, choices among these dimensions are likely to change with changing public attitudes and changing availability of various land-use benefits.

If, on the other hand, current trends continue toward greater public participation in goal setting, then continuous public participation will identify shifts in preference patterns.[5/] In this case, the most important research for dealing with landscape amenity will concern (1) methods for helping representatives of the public understand the choices available and (2) methods for identifying relative importance of alternative management patterns.

Research on public understanding of choices should evaluate ways of communicating or displaying complete information on the consequences of alternative management actions. It should also examine the effects of different information on people's acceptance of specific management actions.

Research to establish relative importance of different environments will require forced choices on the part of respondents. The most difficult aspects of such research 'will be getting respondents to understand the sets of consequences involved in choices and then to make the same choices in experimental settings that they would in "real world" settings.[6/]

INTERIM GUIDELINES

Although research can provide an increasing number of answers, decisions concerning forest debris must be made now, and these require interim guidelines. The guidelines listed below should be considered whenever recreational and esthetic values require special measures for dealing with forest debris.

Because opportunities for dealing with the amenity effects of forest debris involve much more than remedial treatment of existing debris, guidelines are presented under the headings of broad management planning, manipulation of forest debris, and management of forest visitors.

BROAD MANAGEMENT PLANNING

1. Where possible, keep logging slash and amenity uses of the forests separate in both space and time. This will mean searching for zoning opportunities that permit timber to be provided on the most productive sites, thereby entirely freeing other sites for the production of amenity values.. It may also mean constructing or relocating recreation facilities to keep them in the most attractive stages of a rotation.

2. Lengthen rotations in critical view areas to reduce the proportion of a working circle with exposed slash or bare ground. Lengthened rotations will also reduce the frequency' of facility relocations as suggested in guideline 1 above.

5/ Private owners can be expected to watch reaction to public forest decisions for evidence of what is acceptable practice.

6/ Many studies have shown that people's answers to hypothetical situations tend to be unreliable guides to what they will do if forced to make similar choices in the marketplace or other real world settings (Potter et al. 1972).

3. Reduce the scale of slash relative to nearby trees by (a) using partial harvesting methods, (b) leaving islands or clumps of trees within cutting areas, or (c) keeping clearings small.

4. Where clearcutting is practiced, increase the "legibility" of sustained yield forestry by dividing each working circle into a series of "visual management units." These units should have harvesting scheduled to (a) make regeneration and a succession of age classes obvious to the casual observer and (b) leave not more than 10 percent of each unit without tree cover at least 3 or 4 feet tall. Increasing "legibility" will help people see that slash and bare ground are a small and temporary portion of a total process.

5. Keep individual clearings small enough that a variety of age classes will fit readily into a visual management unit as mentioned in guideline 4.

6. Where highly productive sites are dedicated primarily to even-aged timber management, create a coarse-textured landscape so that new cuttings and areas of debris remain a part of "ground" rather than becoming "figure."

7. Soften the edges of cutting and slash areas by (a) using irregular shapes, (b) orienting openings for minimal visibility from common viewing points, (c) using partial harvesting systems where practicable, and (d) "feathering" the edges of clearings. Feathering can be accomplished either by partial harvesting in a band around each opening or by harvesting this band enough ahead of time to provide a border of young trees between the clearing and adjacent timber.

8. Have all cutting areas designed by a landscape architect. This will mean giving landscape architects and foresters equal responsibility and authority in the design and layout of cutting areas.

MANIPULATION OF FOREST DEBRIS

Treatments to reduce the undesirable amenity effects of forest debris involve a tension between order and naturalness. Where an appearance of naturalness can be achieved, as under partial harvesting with small volumes of slash, it is much preferred. However, if apparent naturalness is clearly unlikely, as in clear-cutting of old growth with large volumes of slash, then it is important to create an orderly scene that shows viewers the land is being "cared for." Specific guidelines to consider include:

9. Where volumes of debris are small, enhance the appearance of naturalness and hasten rates of decomposition by (a) leaving a residual stand, (b) lopping and scattering, (c) crushing, (d) chipping, (e) piling and burning, or (f) burying.7/ (See Aho 1974.)

7/ A forest pathologist should be consulted before material is buried. Otherwise, a reservoir of pathogens may be created to infect the next stand. (Information from personal communication with Professor Charles H. Driver, College of Forest Resources, University of Washington, Seattle, May 1973.)

10. For heavy volumes of debris, create an appearance of "managed concern" by (a) yarding unmerchantable material, (b) windrowing, or (c) piling. Burning may be appropriate after material has been concentrated (Martin and Brackebusch 1974).

11. Avoid appearances of waste and inefficiency by increasing utilization. This may require subsidizing utilization by at least as much as equivalent remedial treatment of debris would cost.

12. Where firewood is in demand, open slash areas to firewood collection and advertise the fact.8/

MANAGEMENT OF FOREST VISITORS

Two general patterns of visitor management can help reduce the effects of forest debris on amenity values. The first is to guide visitors away from unattractive areas, as suggested in guideline 1. The second is to help people understand what they see. Explanations to convince people that "good forestry" is being practiced will be most effective when all stages of a rotation are clearly in view, as suggested in guidelines 4, 5, and 6. Guidelines for helping people avoid or understand debris areas are as follows:

13. Identify and mark "scenic routes" that avoid areas of slash and bare ground along secondary road systems. Such routes will need to be modified from time to time as rotations progress. Roads into especially unsightly areas may need to be blocked.

14. Relocate trails to avoid unsightly stages of rotations.

15. Create overlooks or short tours that permit a visitor to see all stages of sustained yield timber management--including slash and bare ground--within a small area.

16. Use booklets, audio stations, cassette tape tours, short-range radio transmitters (received through visitor's car radio), or other means to help people understand what they are seeing. In such communications, messages must be rewarding to the visitors. Consider "Why would he find this interesting?" not just "What do we want him to know?"

The interim guidelines presented above offer no quick and easy solutions to a growing problem. Some of them deviate substantially from conventional practice. Many involve new costs that must be weighed against benefits. But until research and perhaps public participation in decisions can clarify relative priorities, these guidelines identify the major opportunities for reducing the recreational and esthetic problems caused by forest debris.

8/ Suggestion from Russell M. Fredsall, Western Wood Products Association, May 1972.

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BRUSHFIELD RECLAMATION AND TYPE CONVERSION

H. Gratkowski

ABSTRACT

Approximately 4.4 million acres (1.8 million ha) of commercial forest Zand in the Pacific Northwest are occupied by brushfields or weed trees. In addition, another 2.8 million acres (1.1 million ha) are in we22 stocked stands of red alder and bigleaf maple. The rapidly increasing demand for forest products in this Nation and throughout the world makes it urgent that this Zand be reclaimed and reforested with productive young stands of conifers.

Brush composition varies from tough evergreen chaparral on highly productive Douglas-fir coastal sites in southwest Oregon to a predominance of deciduous species on dry ponderosa pine sites in eastern Washington. In the Coast Ranges, hardwoods vary from evergreen tanoak and Pacific madrone in southwest Oregon to the deciduous red alder and bigleaf maple in western Washington.

Site preparation in the Pacific Northwest thus far has involved mechanical scarification or eradication, prescribed burning, and application of herbicides; but combinations of methods have proved necessary in reclamation of most brushy sites. It seems reasonable to expect that silvicultural, reclamation, and type conversion operations on these lands will produce 150 to 200 million tons (136 to 181 million metric tons) of woody plant residue that must be burned, shredded, mulched, or destroyed in the process. Effects of the shrub and hardwood communities on Zand management and disposal of shrub and weed tree residues must be considered in appraisal of forest residue problems.

Keywords: Brushfield reclarnation--brush control, herbicides; site preparation.

INTRODUCTION

Extensive areas of rough mountainous terrain in Oregon and Washington are more suitable for timber production and recreation than for any other use. Fertile soils are combined with a relatively mild climate, heavy rainfall, and native conifers that attain exceptionally large size at maturity. As a result, this area--especially the Douglas-fir region west of the crest of the Cascade Range--has the greatest concentration of highly productive forest land in the Nation (USDA Forest Service 1965a).

However, the Pacific Northwest also has a rich flora of other vegetation with an abundance of aggressive shrubs and weed trees that quickly occupy new burns and cuttings not immediately reforested with conifers. The same conditions that make the region productive forest land also favor ecesis and growth of this competitive vegetation.

Approximately 6 million acres (2.4 million ha) of commercial forest land in the Pacific Northwest are now occupied by brushfields, weed trees, and stands of undesirable hardwoods (Gratkowski et al. 1973). This land must be reclaimed and reforested in the near future, if we are to provide an adequate supply of forest products 50 to 100 years from now. But land occupied by other vegetation requires treatment to reduce vegetative competition before reforestation or before conifer stocking can be increased to an acceptable level. Eradication and other site preparation treatments will produce large amounts of forest residues that must be disposed of during reclamation.

EFFECTS ON LAND MANAGEMENT

Brushfields and brush control problems affect forest, wildlife, watershed, and range management. Brushfields and stands of weed trees reduce income and add to cost of administering productive lands, Most land managers, therefore, are interested in converting brushfields to more productive types of vegetation wherever possible and economically feasible.

On forest land, brush species and weed trees compete with more desirable trees for light, soil moisture, and nutrients. As a result, forest landowners suffer economic losses through delayed stocking, understocking, and reduced growth of trees of all ages. Brushfields also harbor animals, insects, and other forms of life that can be detrimental to trees. Some shrubs are alternate hosts for diseases that cause large financial losses and eliminate excellent tree species from silvicultural consideration in areas where they would otherwise be desirable components of mixed conifer forests. And although some native trees and shrubs such as alder and ceanothus1/ fix atmospheric nitrogen (Rodriguez-Barrueco and Bond 1968, Bond 1967), many have only limited favorable effects on soil and some have allelopathic effects on other species, resulting in a sparse vegetative cover that allows erosion to occur (Gratkowski 1961a).

Fire control can be especially troublesome in brushfields; for such areas require protection and lack access, making fires difficult to control. Chaparral, especially, is noted for its flammability (Plummer 1911, Buck 1951). Chaparral not only burns with intense heat, but construction of firelines is a laborious process, fire fighters are hampered and restricted, and escape in emergencies can be impossible.

Watershed managers prefer a plant cover that will maintain or improve the site while yielding maximum amounts of usable water throughout the year. If

1/ Scientific and common names are listed at the end of this chapter.

several types of vegetation will accomplish this equally well, the type that will produce the greatest economic return in merchantable products is preferred. Brushfields stabilize soil and protect a watershed from erosion but yield little or no economic return; this limits funds available for development of roads and other access for fire protection, stream maintenance, and erosion control. As a result, large fires and subsequent excessive erosion are more apt to occcur and adversely affect water quality on brush covered watersheds than on forested watersheds.

Finally, many northwestern shrubs and weed trees are valuable browse and food plants for cattle, sheep, and wildlife (Dayton 1931), while others only provide cover and have little browse value. Selective grazing can eliminate desirable browse species and allow the less desirable species to occupy the sites. In addition, many of the least desirable species are aggressive and occupy sites so completely that they exclude more desirable vegetation from the area.

However, brush species and weed trees should not be considered completely undesirable on forest lands. They are natural components of all forest communities, and many undoubtedly have beneficial influences in forest ecosystems that have not yet been detected in our limited ecological studies. As stated earlier, trees and shrubs of several genera (*Alnus, Ceanothus, Cercocarpus*) fix atmospheric nitrogen and improve soil fertility. Shrub communities also provide excellent cover for wildlife; and many shrubs, such as deerbrush ceanothus and redstem ceanothus, are excellent browse species. Others--serviceberry, elderberry, and cherry, for example--provide food for wildlife. Fruits of some shrubs are even considered delicacies by man; special efforts are being made to perpetuate and manage huckleberry brushfields on Mount Adams.

A great number of shrubs and hardwoods are also esthetically desirable for their flowers, foliage, and form. These should be retained for their beauty in and about recreation areas and travel routes.

In the southern portion of the Douglas-fir region, especially on south and southwest slopes, many shrubs serve as nurse crops for young conifers, providing shade and ameliorating harsh microclimatic conditions to a degree that favors survival and establishment of coniferous tree seedlings. And in forest cuttings, retention of shrubs that are desirable browse species may also reduce browsing of conifers by wildlife.

CURRENT KNOWLEDGE AND PRACTICE

Brushfield reclamation and type conversion on a major scale are relatively recent silvicultural activities in the Pacific Northwest; vegetation control at reasonable cost became possible with the discovery of the phenoxy herbicides 2,4-D (2,4-dichlorophenoxyacetic acid) and 2,4,5-T (2,4,5-trichlorophenoxyacetic acid) about 25 years ago. Before that, mechanical eradication was the only practical method of site preparation for brushfield reclamation, but it was expensive. And without effective, inexpensive tools such as herbicides to insure survival and dominance of the planted conifers, most areas were rapidly reoccupied by brush species. Further, the availability of large supplies of old-growth timber at low stumpage prices made such investment of management funds relatively unappealing to timberland owners.

However, reduction of our timber resource, 'increased demand for forest products, and greatly increased stumpage prices during the past 30 years are causing foresters and landowners to reconsider reclamation of land occupied by brush species and weed trees. Many foresters are already engaged in reclamation and type conversion. More will follow as effective and economical methods are developed.

EXTENT OF PROBLEM AREAS

Precise figures for acreage occupied by brush species and weed trees are not available. However, Forest Survey figures'indicate that at least 4.4 million acres (1.8 million ha) of commercial forest land in the Pacific Northwest are now either nonstocked or poorly stocked with desirable tree species (USDA Forest Service 1965b).2/ Approximately 1.3 million acres (0.5 million ha) are nonstocked; and 3.1 million acres (1.25 million ha) are so understocked that other vegetation is undoubtedly predominant on the sites.

In the Pacific Northwest, commercial forest land that remains nonstocked by conifers for several years will be occupied by other forms of vegetation. Experience indicates that this vegetation must be removed or\ reduced in density before the sites can be reforested. Similarly, land with only small numbers of conifers almost invariably are predominantly occupied by native shrubs, forbs, grasses, or weed trees. This competition, too, must either be reduced or be eliminated before the sites can be reforested or stocking can be improved.

In addition to the 4.4 million acres (1.8 million ha) nonstocked or poorly stocked with conifers and hardwoods, at least an additional 2.4 million acres (1.0 million ha) of highly productive commercial forest land in the Oregon and Washington Coast Ranges are occupied by medium to well-stocked stands of red alder. Another 0.4 million acres (0.2 million ha) are stocked with bigleaf maple.

Alder is now logged and sold whenever possible. Under present conditions, however, markets are limited, and several investigators have concluded that most sites occupied by alder should be reclaimed and converted to conifer production (Ker et al. 1960, Smith 1968, Yoho et al. 1969). Under programs such as RESTOR, a reclamation program advocated by the Oregon-Washington Silvicultural Council, most of the 2.4 million acres (1.0 million ha) occupied by alder would be added to the 4.4 million acres (1.8 million ha) of brushfields and weed trees cited earlier. This would increase extent of brushfield reclamation and type conversion problem areas to more than 6 million acres in the Pacific Northwest.

If conversion of alder sites to conifer production is contemplated, conversion should initially be limited to young stands of alder and to sites where

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2/ This estimate includes 85 percent of the commercial forest land classified as nonstocked and 50 percent of the land classified as poorly stocked. Fifteen percent of nonstocked land was considered as new burns and cuttings that had not had time to reforest. The 50 percent of land classified as poorly stocked is considered to represent land only 10 to 24 percent stocked with desirable tree species.

alder will not attain marketable size. Inevitably, site preparation and type conversion of these lands will add large volumes of forest residue to the disposal problem.

BRUSH AND HARDWOOD TYPES

A great variety of shrubs and hardwoods is represented in these plant communities. Along the coast, they vary from evergreen, broad-sclerophyll forests of tanoak and madrone in the south to red alder and bigleaf maple forests in the north. Brush communities vary in composition from deciduous species in the northern Cascade Range to mixed evergreen and deciduous species in the southern Cascade Range (fig. 1), with a true chaparral in the Rogue River valley. East of the Cascade Range, evergreen species predominate in most brushfields except those in the Okanogan highlands.

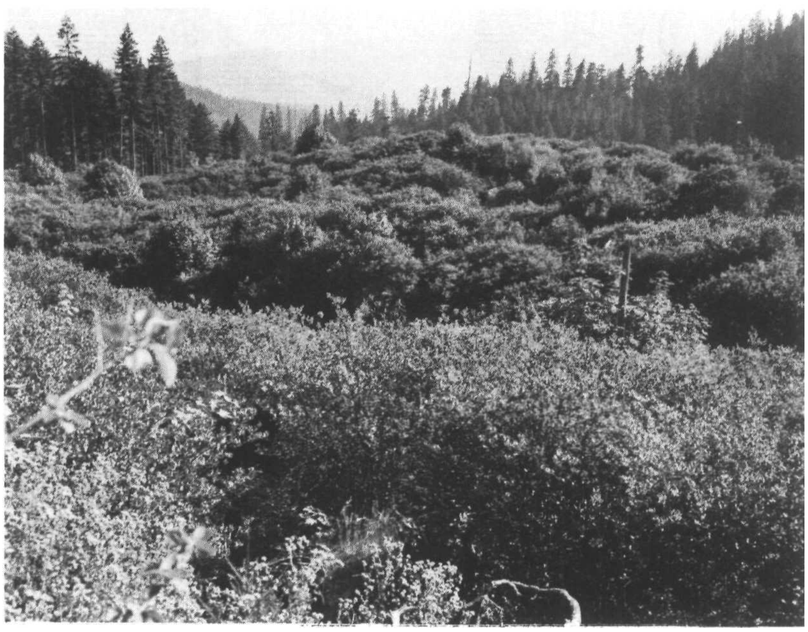

Figure 1.--Dense, relatively pure stand of varnishleaf ceanothus interspersed with bigleaf maple on a clearcut in the Cascade Range.

These plant communities reflect a corresponding variation in soil, topographic, and climatic conditions (fig. 2). This variation in habitats is further .reflected in major differences in coniferous forest types. As a result, management and manipulation of the myr'iad combinations of shrubs and hardwoods to favor establishment and growth of selected coniferous species in Pacific Northwest forests call for extrememly sophisticated--and in many cases, expensive--silvicultural techniques.

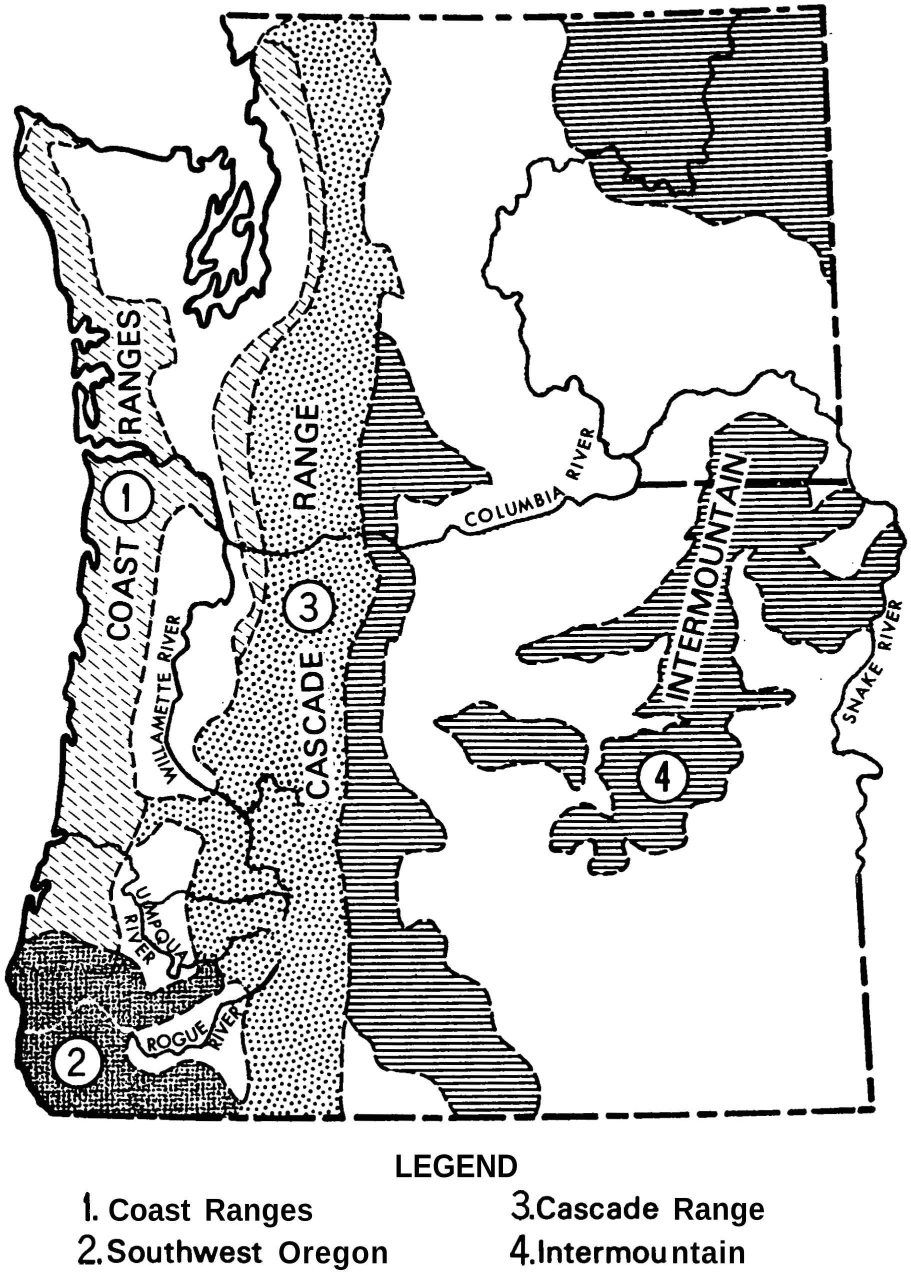

Figure 2.--Brush and hardwood problem areas in the Pacific Northwest.

Coastal.--In the Oregon-Washington Coast Ranges and foothills of the Cascade Range in Washington, red alder and bigleaf maple are the dominant vegetation on 2.8 million acres (1.1 million ha) of highly productive forest land (Metcalf 1965). In addition, brushfields composed of shrubs such as salmonberry, thimbleberry, vine maple, hazel, elderberry, evergreen huckleberry, and salal occupy another 500,000 acres (202,350 ha). Conifers are capable of rapid growth and development on almost all this land. At least 2.5 million acres (1.0 million ha) should be reclaimed and reforested with conifers.

Southwest Oregon.--Approximately 1.0 million acres (0.4 million ha) of productive forest land in the Coast Ranges and Siskiyou Mountains of southwestern Oregon are occupied either by broad sclerophyll forests of tanoak and Pacific madrone with an understory of evergreen shrubs or by an evergreen chaparral of manzanitas, ceanothus, tanoak, canyon live oak, and other shrubs.

Chaparral is the climax vegetation on many sites in the dry interior portion of the Siskiyou Mountains and on most areas at low elevations in the Rogue River valley (Detling 1961). Such sites should not be afforested.

However, wetter sites in the western end of the Siskiyou Mountains and along the coast are occupied by broad-sclerophyll forest and chaparral that appear to be fire-induced subclimaxes. Coniferous forests naturally succeed these seral stages where conifer seed sources are present. Where coniferous seed sources are absent or inadequate, many sites near the coast can be reclaimed and reforested using techniques already available. Although expensive, the investment is justified. The coastal sites are among the most productive forest lands in the Pacific Northwest.

Cascade Range.--Brushfields also occupy about 1.0 million acres (0.4 million ha) of commercial forest land in the Cascade Range. As in the Coast Ranges and Siskiyou Mountains, evergreen trees and shrubs are predominant in the southern end of the Cascade Range. Various species of ceanothus and manzanita form relatively pure brushfields or grow in combination with golden chinkapin, Sierra evergreen chinkapin, quaking aspen, willows, bitter cherry, serviceberry, huckleberries, and *Ribes* species. Northward, especially at low elevations, the proportion of deciduous species increases. In Washington, deciduous species predominate.

Intermountain.--Another 1.6 million acres (0.6 million ha) of brushfields and understocked stands are found in the ponderosa pine region of eastern Oregon and Washington. Most troublesome are snowbrush ceanothus, Sierra evergreen chinkapin, and a nonsprouting form of greenleaf manzanita. Included in this area estimate are the predominatly deciduous brush areas of the Okanogan highlands in northeastern Washington, where smooth menziesia, Rocky Mountain maple, mallow ninebark, willows, and snowbrush ceanothus are prevalent.

These areas are colder, drier, and have a much lower productive potential than forest lands along the coast and on the west slope of the Cascade Range. However, in total, they can produce a considerable volume of timber that will be urgently needed in the future. They should be reclaimed and reforested as soon as economically feasible.

CONVERSION AND RECLAMATION METHODS

Brushfield reclamation and type conversion methods vary in the Pacific Northwest depending upon terrain, species and density of vegetation, and objectives of management. Mechanical eradication, prescribed burning, and chemical brush control are the primary methods of site preparation. On most sites, combinations of treatments have proved necessary to attain adequate control of competitive vegetation to insure survival of planted conifers. Site preparation methods have been reviewed and discussed by Schubert and Adams (1971) and by Gratkowski et al. (1973). However, a brief consideration of the methods is desirable, for choice of method determines effects on the site and influences type, volume, and distribution of resultant residues.

CHEMICAL BRUSH CONTROL

Chemical brush control is widely used to release young conifers from all forms of competing vegetation and to prepare sites for reforestation. To date, however, its greatest use has been in release treatments rather than in site preparation.

Herbicides are usually applied as aerial sprays in water, oil, or oil-in-water emulsion carriers. By far the most widely used herbicides are low volatile esters of 2,4-D and 2,4,5-T. Application rates are usually 1 to 3 lb. acid equivalent per acre. Helicopters are used in applying the sprays, for their flight characteristics are better adapted than those of fixed-wing aircraft for aerial spraying in mountainous terrain.

In release treatments, no disposable wood residues are created. The dead plants are allowed to break down, fall, and decay in place. On new burns and cuttings, release sprays are usually applied early in the life of the stand, stems are small in diameter, and residues are limited in amount. Although fire hazard is increased for a time and many consider the dead plants esthetically undesirable, small shrubs break down and decay in a few years. However, when the trees are in well-established, mature stands of shrubs or hardwoods, decomposition may be slow. In both cases, time required for decomposition will vary with species and climatic conditions.

In contrast, chemical sprays for site preparation are almost invariably applied on dense, well-established brushfields or stands of weed trees. Stem diameters are larger, volumes of residue are greater, and decay takes much longer (fig. 3). Planting of conifers may either precede or follow application of the initial spray. In most cases, however, the initial aerial application of herbicides precedes planting to reduce brush competition, improve conifer survival, and minimize any possibility that the chemicals may damage newly planted young trees.

Chemical site preparation is less expensive than other methods and allows quick and easy treatment of large areas with minimum manpower (Gratkowski et al. 1973), but it has several important disadvantages. Increasing public concern over the possibility of environmental contamination must be given careful consideration. Aerial sprays must be applied precisely within the boundaries of the treatment site and kept out of streams, lakes, and other ecologically sensitive areas. Large areas of standing dead brush are also objectionable and esthetically undesirable, especially near urban or recreation areas.

Figure 3.--Dead tanoak and Pacific madrone remain erect on this site 10 years after aerial spraying to release young conifers from evergreen shrubs and weed trees.

After reforestation, dead brush increases the fire hazard for several years, and this can jeopardize plantations even after the plants begin to break down. In addition, rabbits, hares, and other browsing animals are protected from predators and move about freely under dead brush. Where such animals are abundant, this can be a major disadvantage and result in loss of most of the planted trees. The chemically killed brush may have to be burned or mechanically eradicated before planting.

PRESCRIBED BURNING

Prescribed burning of chemically desiccated brush is increasing as a method of site preparation. Any merchantable conifers and hardwoods are first removed. Unmerchantable trees are then felled to add to the low fuels, to provide a more compact fuel mass, and to decrease the fire hazard during burning. Dinitro (ammonium dinitro-sec-butylphenate), phenoxy herbicides, or other sprays are then applied as desiccants to defoliate or kill residual vegetation and increase its flammability. When a quick-acting, contact herbicide such as dinitro is used--or in the Coast Ranges, where brush species recover quickly--desiccated brush is burned before the end of the first summer. When phenoxy herbicides are applied in other parts of the Pacific Northwest, maximum shrub kill and desiccation, more complete fuel consumption, and cleaner, easier-to-plant areas are obtained if desiccated brush is burned at the end of the second summer. Burning also sets back resprouting shrubs a second time.

In stands of low, brittle-stemmed brush species, desiccation can also be accomplished by crushing and compacting the shrubs with tractors (Bentley et al. 1971) or with tractors towing Marden brush cutters or similar equipment. Herbicides may be applied before crushing to kill and desiccate the shrubs and speed the crushing process. The dead shrubs are more easily and quickly broken down by mechanical equipment.

Effects of burning on site factors and the environment are covered in the other papers of this compendium and in many articles and papers published during the past 50 years (Ahlgren and Ahlgren 1960, Isaac and Hopkins 1937, USDA Forest Service 1972, etc.). However, burning of brushfields differs in many ways from burning of logging slash. Fuels are generally smaller in size and much more evenly distributed over the area. Fuel distribution and types are more like those in wildfires, but the dense concentration of highly flammable fuels near the surface is consumed within a very short time. This is especially true when burning chemically desiccated brush.

Prescribed burning of desiccated brush usually involves greater volumes and more complete disposal of residues than any other method of site preparation. Residues may range from as little as 20 tons per acre (45 metric tons/ha) in small-stemmed stands of low brush to 40 or 50 tons per acre (90 or 112 metric tons/ha) in dense brush with some weed trees. Residues may exceed 70 tons per acre (157 metric tons/ha) in many stands of alder, bigleaf maple, or other hardwoods.

Prescribed burning has several advantages. It produces large, clear areas that are easily planted. Many problem areas are in mountainous terrain too steep for mechanical eradication. Such areas can only be effectively and economically prepared for reforestation by prescribed burning (fig. 4). Chemical site preparation can also be used on steep terrain, but spraying is not effective in shrub communities in which species resistant to herbicides are abundant. Spraying only removes susceptible species. It releases resistant shrubs and leaves them to occupy the site, so that later release of planted trees is much more difficult and expensive. In contrast, chemical desiccation followed by controlled burning burns out the dead shrubs and trees, kills the crowns of resistant species, and clears the site enough to allow planting of conifers. Properly timed, fire will also set back resprouting shrubs a second time, further deplete food reserves stored in the roots, and reduce later resprouting and competition. Since herbicides are generally more effective on sprouts than on mature shrubs, release sprays can be used to maintain dominance of planted conifers over resprouting brush and other vegetation reoccupying the prepared site.

However, controlled burning also has several major disadvantages. Smoke pollution is unacceptable in some areas such as the southern end of the Willamette valley. But smoke reaching urban areas can be minimized by burning under proper meteorlogical conditions, when convection columns will carry smoke to high elevations and disperse it through deep layers of unstable air where wind will carry it away from densely populated areas (Dell and Green 1968, Cramer and Graham 1971). Charred and blackened areas may also be esthetically undesirable near urban areas.

Burning is not advisable on highly erosive soils, and erosion may also occur on other soils if fires aye so intense that the soil surface is completely denuded and roots and other organic matter are burned out. Although many shrub species resprout if fires are less intense and do not kill the roots and root crowns, most sprouts and brush seedlings are easily controlled with inexpensive herbicidal sprays. Finally, burning may also be undesirable adjacent to high value or high hazard areas, where escapes or spot fires can result in large financial losses or be especially difficult to control.

Figure 4.--Young Douglas-firs in open on an old skid trail where logging debris was removed before slash disposal. The tall, dense cover of varnishleaf ceanothus shrubs in the background shows where logging slash was broadcast burned, inducing germination of ceanothus seeds in the soil.

Despite its disadvantages, prescribed burning will probably be a necessary part of treatment in reclaiming much of the forest land occupied by brush species and weed trees in the Pacific Northwest.

MECHANICAL ERADICATION

Mechanical eradication of brush species has been the most widely used method of site preparation in the Pacific Northwest. Large tractors equipped with toothed brush blades have proved most suitable for such work. Eradicated brush is either piled or windrowed on the site.

Use of tractors, however, is necessarily limited to slopes with gradients of 30 percent or less. Although some 35-percent slopes have been treated, tractors must work up and down slope to minimize danger of overturning the equipment. On such slopes, less acreage can be cleared per hour, and less complete clearing is sometimes accepted as an alternative. However, undisturbed brush between cleared lanes and patches can harbor rabbits and other animals that need move only a short distance into the open to clip planted trees (Gratkowski and Anderson 1968). Cleared lanes have also served as passageways for deer and cattle that browse and trample young trees (Gratkowski 1961a). On many National Forests, complete clearing is preferred to reduce animal damage, minimize brush competition, and increase plantation survival.

Volumes of debris burned on mechanically cleared sites are usually less than those burned in chemically desiccated brushfields. Although total volumes of residue may be the same as on sprayed-and-burned sites, many piles and windrows on mechanically cleared areas need not be burned unless tree-eating animals are abundant and the piles might harbor animals that would threaten survival of the plantation.

Complete mechanical eradication is probably the most effective of all methods of site preparation for survival of young conifers. Nonsprouting species are eliminated, sprouting species are drastically set back, and the trees are provided full sunlight and reduced competition for limited soil moisture during the dry summer season. Selective aerial sprays can be used later to kill new brush sprouts and seedlings and insure dominance of the young conifers. Unlike chemical site preparation or prescribed burning, mechanical eradication does not leave esthetically objectionable standing dead brush nor blackened, scorched areas.

On the other hand, mechanical eradication is usually the most expensive method of site preparation. Loose topsoil on denuded slopes is also subject to erosion during the winter following treatment, and even a small amount of soil movement can discolor streams and rivers for miles after leaving the disturbed area. In addition, surface soil--especially soils with a high clay content--may be compacted by the heavy equipment, if clearing is done during wet weather.

TREATMENT AFTER REFORESTATION

On all sites, invading vegetation, new germination, and resprouting brush and weed trees can compete severely with conifers for light and for limited soil moisture during the dry summer season. Aerial sprays can be applied to reduce this competition and increase survival of the young trees. Such sprays are usually applied within 1 to 4 years after planting, before competition becomes serious. No residue disposal problems are created. Stems are small, amounts are limited, and the residues can be allowed to fall and decay on the site.

VOLUME OF RESIDUES

RECLAMATION AND TYPE CONVERSION RESIDUES

Biomass data for Pacific Northwest brush and weed tree communities are practically nonexistent. However, similar brush types in California (Bentley 1967, Green 1970, Bentley et al. 1971) and other areas provide a minimal basis for estimates of dry matter per acre as listed below:

Type	Tons of dry matter/acre[3/]
Red alder, bigleaf maple, understory shrubs	30 to > 80
Broad-sclerophyll forest (tanoak madrone)	50 to > 75
Chaparral with some tanoak and madrone	50
Chaparral (coastal)	40
Mixed coastal deciduous and evergreen brush	35
Varnishleaf or blueblossom ceanothus	35
Chaparral (interior)	30
Snowbrush, deerbrush, redstem ceanothus	25
Mixed deciduous brushfields in Cascade Range	25
Manzanita, snowbrush, and Sierra chinkapin	24

Preliminary calculations (Table 1) indicate that potential brush and weed tree residues from brushfield reclamation and conversion of hardwood stands could approach 240 million tons (218 million metric tons), dry weight. Of course, not all such residues must be destroyed. Where conifers are planted under chemically killed brush and weed trees, dead shrubs and trees ar4 allowed to drop and decompose on the site. And on mechanically cleared areas where small mammals will not threaten survival of planted conifers, piles and windrows need not be burned. Even so, it seems logical to expect that at least 150 to 200 million tons (136 to 181 million metric tons) of brush and weed tree residues must be burned or otherwise disposed of during brushfield reclamation and type conversion operations in the Pacific Northwest.

3/ Estimates are for all aerial parts of trees and shrubs plus litter.

Table 1.--*Estimate of potential brush and weed tree residues from brush control, brushfield reclamation and type conversion operations in Oregon and Washington*

Area	Acres	Average residue per acre[1/]	Total residue dry weight
		- - - - - - - - - - Tons	- - - - - - -
Coastal	2,500,000	50	125,000,000
Southwest Oregon	1,000,000	45	45,000,000
Cascade Range	1,000,000	30	30,000,000
Intermountain	1,600,000	24	38,400,000
Total	6,100,000 (2,468,670 ha)	--	238,400,000 (216,276,480 metric tons)

1/ Estimates of average residues based upon distribution of plant communities and average density of brush and weed tree types in the designated areas.

SILVICULTURAL RESIDUES

Cultural residues of brush and weed trees also require consideration. Such residues will result from silvicultural treatments: (1) to release young stands of conifers from overstories of brush and weed trees, (2) to increase growth rates of trees in older stands by controlling brush understories, or (3) to release trees growing in association with less desirable hardwoods by eliminating the hardwoods and less desirable conifers with herbicides or silvicides. Release and increased survival and growth of desirable conifers are achieved by reducing competition of other vegetation for light and for soil moisture during the dry summer season. Competition for nutrients is probably less detrimental than that for light and moisture on most northwestern forest soils. Alternative silvicultural methods for handling these problems are presented in table 2.

In well-stocked young stands, management has several choices. It may elect to do nothing, balancing any reduction in growth rates against cost of release treatments and interest on the investment. Even if release treatments are elected in well-stocked pole-sized or younger stands, no residue disposal problem will be created, since the dead material is allowed to break up, fall, and decay in place. Fire hazard, however, may be increased for several years after treatment.

In understocked stands, however, volumes of residue may equal or even exceed those resulting from reclamation of nonstocked sites. This is especially true in pole-size and old-growth stands where snags, decayed trees, and logging debris may add greatly to residues of lesser vegetation. Residues on such areas can easily exceed 100 tons per acre (224 metric tons/ha).

It must also be noted that many new burns and cuttings are being occupied by brush species and weed trees due to failure of reforestation efforts and lack of adequate natural seed sources. Reclamation of these sites will add appreciable volumes of residues to our disposition problems in the future.

Furthermore, a recently announced U.S. Forest Service policy is to seek out National Forest lands that have been seeded or planted with offsite stock and reforest them with more suitable trees. Many plantations of offsite stock have already failed, and the sites are occupied by native shrubs and weed trees. Others were probably classed as medium or well stocked even though the trees were not growing well and obviously were not suited to their new environment. Such areas must be reclaimed and reforested with stock from appropriate seed sources under the new policy. At this moment, no reasonably reliable figures for such acreage or volumes are available. However, it is obvious that additional volumes of residues will be created and must be disposed of in reclaiming these sites.

Luckily, many such areas have seeded in naturally from adjacent native seed sources and are now well stocked with young trees adapted to the site. On such areas, young offsite trees can be removed in normal thinning and cleaning operations. On some sites, silvicides might be used to kill older, offsite trees so that the weak trees will not serve as hosts for insects and diseases that may then infest and infect the new native stock.

Where young, pole-size trees of offsite stock are involved, marketable material can be harvested and sold. However, special care must be exercised that good, genetically suitable young trees that have naturally seeded in on

Table 2.--*Silvicultural* **choices in stands** of **conifers** *with brush* **understories or growing** *amid* **shrubs** *and* **weed** *trees*[1]

Age of stand	Stand condition	
	Understocked	Medium or well stocked
Old growth	1. Harvest and reforest a. harvest all merchantable trees b. prepare site for reforestation c. reforest with suitable conifers	(No problem)
Pole-size	1. No treatment, or 2. Harvest and reforest a. harvest all merchantable trees b. prepare site for reforestation c. reforest with suitable conifers 3. Improve stocking a. control brush and weed trees to release the conifers b. interplant to increase conifer stocking	1. No treatment, or 2. Release conifers to improve growth rates a. if competition is hardwoods with crowns exposed between those of the conifers, control hardwoods with aerial spray or by hack-squirt, basal spray, mist blower, or other use of herbicides b. if competition is in understory, use selective method such as hack-squirt, basal spray, mist blower, or other treatment in understory
Seedling and sapling	1. Release trees to improve conifer growth rates, or 2. Release and improve conifer stocking a. control brush and/or weed trees b. interplant to increase conifer stocking 3. Reclaim and reforest a. prepare site for reforestation b. replant with suitable conifers	1. No treatment, or 2. Release conifers with selective aerial spray

[1] On all sites where young conifers are planted, apply herbicidal spray whenever needed to control regrowth of competing vegetation and insure survival and growth of the young trees.

these areas are not destroyed in the process, reducing stocking below desirable levels. If this might occur, it may be best to kill both merchantable and unmerchantable offsite trees by injecting them with silvicides such as cacodylic acid, picloram, or amines of the phenoxy herbicides. Residues may be disposed of in the same way as other thinning slash, or treated trees may be left standing to break up and decompose on the site. First, the finer dead branches will break off, then larger and larger branches and limbs, until only snags are left to fall between the vigorous young conifers. This will minimize damage to the new young stand. It may be desirable to fall the snags to reduce fire hazard, but decomposition in place simplifies disposal problems.

HARDWOOD HARVESTING RESIDUES

Harvesting residues are derived from two main sources in stands of Pacific Northwest hardwoods--most from harvesting red alder but some from chipping tanoak for pulpwood.

Unfortunately, all alder in a stand is not uniform in size nor equally sound. As a result, unmerchantable trees and residual brush must be disposed of to reduce the fire hazard and prepare the sites for planting. After the merchantable trees are removed, unmerchantable trees are felled to add to brush and logging slash fuels, and residual live brush is desiccated with herbicides. Slash, felled trees, and desiccated brush are then burned to prepare the site for reforestation with conifers. On such areas, weight of residues burned may range from 50 to 100 tons per acre (112 to 224 metric tons/ha).

It is possible--even probable--that technological advances will develop new and increased markets for alder wood and fiber. If this does occur, it may act in two ways to reduce volumes of alder residues in the future.

First, although alder stumpage prices are low and the market is more limited and fluctuates more than that for conifers, alder approaching marketable size is being held by many landowners who hope that markets will develop before the stands break down. Sale of this material would help offset conversion costs and reduce volumes of residue to be destroyed in type conversion. Unfortunately, alder is a short-lived species. Stands begin breaking down when 50 to 70 years old, depending upon site conditions (Smith 1968). Many stands will undoubtedly disintegrate before demand increases enough to absorb all such alder that is available. Unless reforested with conifers at that time, the land may be occupied by semipermanent stands of brush species (Newton et al. 1968)

Second, if new or increased markets for alder are developed, smaller landowners, especially, may favor alder as their forest crop. Full natural regeneration of alder is relatively easy on prepared sites, young alder grows rapidly, and this species allows short rotations that would provide early and more frequent returns to the landowner. In contrast, conifers are often more difficult to regenerate and require longer rotations.

In recent years, tanoak chips have gained favor over red alder for pulp. Full-length tanoak trees up to 16 or 18 inches (40 or 46 cm) in diameter at the butt are felled, yarded to a portable mill on the area, debarked, chipped, and the chips blown into trucks for transport. Residues on the chipper site consist of piles of tanoak bark, chipper dust, and fine particles. These can be scattered or burned in place after the equipment is moved to a new site.

However, another residue problem is created. Many small, unmerchantable tanoaks, madrones, and residual shrubs are left on the logged area. This residual, vegetation must be either mechanically eradicated or felled, sprayed, and burned to prepare the site for reforestation with conifers. If not promptly reforested, the site will revert to a broad-sclerophyll brushfield. Volumes of residue on the logged areas and chipper sites are estimated to range from 30 to 70 tons per acre (67 to 157 metric tons/ha).

RIGHTS-OF-WAY RESIDUES

Two types of rights-of-way also contribute noteworthy volumes to the residue problem: utility rights-of-way and roads. Although neither may contribute large volumes, at least portions of the residue must be disposed of.

Brush and weed tree control along powerline rights-of-way are especially noticeable and esthetically undesirable because the broad, straight swaths extend down mountainsides, across roads and streams, their geometric regularity attracting all eyes as they cut, through the random patterns of natural vegetation. These residues are usually allowed to fall and decay in place. By that time, species resistant to herbicides will have resprouted and increased in proportion, making retreatment necessary. Far more preferable would be type conversion to a permanent cover of low-growing grasses and shrubs that can provide food and cover for wildlife.

Saplings and tall shrubs dangerously obstruct vision on winding forest roads. Along highways, they obstruct scenic views for passing motorists. Roadside brush is frequently sprayed with herbicides; but extensive strips of dead brush, small trees, and damaged conifers detract from the esthetic beauty of roads through woodlands and mountains.

In the past, much roadside brush was manually cut, piled, and burned. Now, hammermill-type shredders and large rotary cutters with movable blades are being tested in an effort to eliminate shrubs and saplings with Jess labor and at lower cost. Although shredders work well on level terrain, they do not seem adaptable to the steep cuts and long fill slopes characteristic of Pacific Northwest forest roads. And rotary cutters do not shred all aerial parts of the plants. They simply chew them off, leave conspicuous shredded stubs, and produce appreciable amounts of residue that should be piled and burned. When rotary cutters are used, spraying the newly cut stubs with herbicides will minimize resprouting and reduce the need for future treatments.

Roadside slash resulting from brush control should be chipped or piled and burned for fire control as well as esthetic reasons. In at least one instance, road construction debris has carried fire from one clearcut to another (Bell [Dell] 1969). Disposition, however, is not a one-time process. Roadsides provide an ideal habitat for successive generations of trees, shrubs, and herbs; and a planned program of maintenance should be standard operating procedure. Where herbicidal foliage sprays are used to control dense roadside shrubs, the chemically killed brush undoubtedly could also act as a fuse carrying fire from cutting to cutting. Lopping and chipping green shrubs to form a roadside mulch might ultimately reduce maintenance by preventing germination and growth of other vegetation. To minimize resprouting, stubs of lopped shrubs should be treated immediately with a 12 aehg 4/ mixture of low volatile esters of 2,4-D and 2,4,5-T in diesel oil.

4/ Twelve lb (5.44 kg) acid equivalent per 100 gallons (378.5 liters) of spray solution; 6 lb (2.72 kg) of 2,4-D and 6 lb (2.72 kg) of 2,4,5-T.

CURRENT RESEARCH

Both volume and type of brush and hardwood residues may be affected by research in progress. Current research seeks more effective herbicides and better methods of application, new methods of mechanical eradication, improved prescribed burning techniques, and technology that will allow use of wood and wood fiber from shrub and tree species that have not been utilized in the past. New developments in the last category could appreciably reduce volumes of residues that must be removed or destroyed.

HERBICIDES AND SILVICIDES

Since discovery of 2,4-D and 2,4,5-T, new plant-control chemicals are .constantly being tested by herbicide manufacturers, industrial foresters, and Federal, State, and industrial research organizations. Broad-spectrum herbicides are sought for site preparation, more selective herbicides are sought to control specific plants without injuring others, and new chemicals are needed to control many species that are resistant to environmentally acceptable herbicides now available.

Discovery of new site preparation herbicides could temporarily increase annual volumes of forest residues. Such chemicals might allow reclamation of many sites occupied by plant communities with species resistant to present herbicides. And if effective new herbicides should be less expensive than those now available, additional acreage might be reclaimed on sites where reclamation is not economically feasible now.

Granular formulations of herbicides such as karbutilate (tert-butylcarbamic acid ester with 3-(m-hydroxyphenyl)-1,1-dimethyl urea potassium cyanate) and picloram (4-amino-3,5,6-trichloropicolinic acid) show promise for site preparation in Pacific Northwest forests (Stewart 1972). Combinations of herbicides have also proved more effective than individual application of each herbicide on many species. Atrazine and phenoxy herbicides, for example, seem to have a synergistic effect that results in increased activity of the chemicals when applied together as an aerial spray to control grasses and forbs in conifer plantations. It seems conceivable that synergistic combinations of other chemicals may also be found in chemicals used to control woody plants in preparing sites for reforestation.

For site preparation, new herbicides must not only control many different plant species; they should also persist only a short time and have little or no undesirable effects on water and soil or on other life forms in the forest environment. After killing undesirable plants, rapid degradation or decomposition of the herbicide is necessary to allow reforestation. Other plant life must also be able to reoccupy the site in order to minimize soil erosion and maintain quality of water from the treated area.

New, more selective herbicides are also being sought to supplement those now available. Such chemicals are used in aerial sprays to release young conifers from competition of grasses, forbs, shrubs, and weed trees without damaging the conifers. New herbicides may extend seasons for safe release of conifers and permit more safety in releasing susceptible species such as pines. In some areas, it is also desirable to selectively control certain shrubs and weed trees without damaging similar plants that are good browse species or provide food and shelter for wildlife. Availability of new chemicals in this category, however, will not increase volumes of residues to be treated, removed, or destroyed. In release treatments, dead shrubs are allowed to fall and decompose among the released plants.

MECHANICAL SITE PREPARATION EQUIPMENT

Four methods have been used for site preparation and type conversion in brushfields. These are: (1) pile or windrow and burn, (2) crush and burn, (3) disk plow, or (4) masticate with hammermill-type flail choppers. Scarification and scattering of residues is a possible alternative where brush is sparse and debris limited. This eliminates burning of residues and still allows proper distribution of planted seedlings.

Large tractors equipped with toothed brush blades have generally proved most effective for eradicating and piling or windrowing brush on suitable terrain in the Pacific Northwest. Forest Service Equipment Development Centers have conducted exhaustive tests of many types of brush rakes, root plows, and add-on teeth or rakes for standard dozer blades (USDA Forest Service 1971).

Crushing breaks down shrubs and small trees so that the plants will die and desiccate. It also compacts the fuel and prepares it for burning. Crushing can be accomplished by sweeping the area with a bulldozer blade carried above the soil surface; blade height is varied depending upon brush species, size, and density. It is especially effective with relatively brittle-stemmed species such as manzanita and is usually more effective on mature brush than on young shrubs. The crushed brush is allowed to dry and then broadcast-burned in place.

Heavily weighted anchor chains have also been dragged across brushfields to crush brush. The chains may be attached between two heavy tractors moving parallel to each other or one end may be attached to a large water-filled steel ball weighing several tons. This last method was tried recently in northwestern California--unsuccessfully--on small tanoak and sclerophyllous brush in an old burn with slopes up to 60 percent. Like bulldozing, anchor-chaining is probably more effective in crushing brittle- and small-stemmed brush species.

Where slopes do not exceed 25 percent, brush may also be simultaneously crushed and chopped into small pieces with rolling choppers such as the Marden brush cutter. These are rolling, water-weighted drums with full-length chopping blades extending from the surface parallel to the axis of the drum. Like crushing, brush choppers are most effective on small- or brittle-stemmed species. It was ineffective on tough, dense, chinkapin in a small trial in southwestern Oregon. On dense, heavy soils, brush crushed with rolling cutters will be compacted and can be burned after it dries. On light pumice soils in eastern Oregon, however, stem fragments were forced into the soil and allowed air movement to dry the soil during the dry summer season. This increased mortality of young pines planted in the treated area.

Disk harrows have also been evaluated by the San Dimas Equipment Development Center. Like the brushland plow, such equipment is designed to chop brush, till the upper layer of soil, and incorporate plant residues and litter in the tilled layer as humus. Like rolling choppers, such equipment is better adapted to gentle terrain and rangeland rather than the steep, rocky, mountainous terrain characteristic of most Pacific Northwest forest land. However, disk harrows are being considered for use on chamise in California.[5] Harrows effectively chop the shrub crowns and tear the burls from the roots, so that most chamise is killed in two passes over an area. Disk harrows are much less effective on dense chaparral and tough species like scrub oak.

A method of partial scarification on steep slopes has been attempted by at least one company. A cable system was used to drag weighted steel drums up and down slope through alder and brush in an effort to open the stand enough to allow planting of conifers. Aerial applications of herbicides were planned to release the trees from residual and resprouting brush and alder.

The San Dimas Center has also conducted tests and field trials of the Tree Eater, a hammermill flail chopping unit in a drum 30 inches (76 cm) in diameter and 72 inches (183 cm) wide. Four rows of cutters, 70 in all, are mounted on four full-length hinge pins. Each flail cutter weighs 14 pounds (6.4 kg). The unit is powered by a 325-hp (330-metric-hp) GMC diesel engine mounted on the back end of a Case 750 tractor with 18-inch (46-cm) tracks and torque converter drive. Operating speed of the cutting unit is 1,800 r/min. The complete unit weighs about 25,000 pounds (17,340 kg). It produces a clean 6-foot (1.8-rn) cleared swath of masticated residue that can serve as a mulch.

However, the Tree Eater has several disadvantages. It has a high center of gravity, and side slope work must be limited to slopes of 20 percent or less. Downhill work should be confined to slopes not exceeding 10 percent, but the Tree Eater can work uphill on slopes up to 30 percent. Breakage and wear of the cutters are high. And where dust may be a problem, an air-conditioned cab may be needed to protect the operator from dust and noise. The Center concluded that the Tree Eater cannot be recommended as a general, large-scale, land-clearing machine.

Disposal of residues created by these various methods depends mostly upon the type of equipment used in site preparation. Crushed and desiccated brush must be burned not only to reduce the fire hazard but to clear the area for planting as well. If sprouts have developed from undamaged roots and root crowns, burning will kill the sprouts and further drain food reserves in the root system.

Piled or windrowed brush also is usually burned, although the fire hazard on such areas is generally far lower than that in crushed brush or in brush killed and desiccated with herbicides. The piles can shelter rabb ts and other small animals that browse trees. Burning the piles or windrows is imperative if browsing animals are abundant.

Burning crushed brush or windrows will result in air pollution that can be undesirable. Burning can temporarily increase available nitrogen in the soil , but it can also result in a loss of some nitrogen from the site. The loss, however, can be offset by application of fertilizer (Mayland 1967). Soil beneath piles and windrows may be heated to temperatures that will burn out humus and organic matter to a depth of a foot or more beneath the surface.

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[5] Personal communication from Lisle Green, Project Leader, Fuel-break project, Pacific Southwest Forest and Range Experiment Station, Riverside, California.

This can reduce soil moisture storage capacity, and planted trees on severely burned sites may suffer from excessive soil aeration. In addition, denuded sites on steep slopes may suffer serious erosion. This can affect quality of water in streams flowing through the burned area, and siltation may kill aquatic insects and larvae in the streams. Soil movement may also bury some trees planted on the denuded slopes (Franklin and Rothacher 1962).

PRESCRIBED BURNING

Electrical ignition techniques and flammable gels developed for slash burning in the past are being tested and adapted for burning desiccated brush (Schimke et al. 1969). Electrical ignition can greatly increase safety of personnel in burning chemically killed brushfields.. Results of meteorological studies to reduce air pollution during slash burning are also applicable when burning crushed or chemically desiccated brush.

Current research is primarily aimed at refining old techniques rather than developing new methods. Picloram and other herbicidal sprays are being tested as replacements for dinitro and other preburn desiccants used in the past. Slash-and-burn techniques are being tried on many areas to gain further experience and refine this method of residue disposal. The log-slash-spray-burn method described earlier is an example of previously developed burning techniques adapted for use on forest land.

UTILIZATION STUDIES

Floral greenery and crude drugs.--Although large volumes of huckleberry, salal, ferns, and other vegetation are gathered for floral greenery in Oregon and Washington, this will not appreciably reduce brush residues. Collecting simply acts as a pruning of the shrubs and the collected material is soon replaced by new growth.

Cascara bark is harvested as a crude drug in the Pacific Northwest. Almost 2 million pounds were gathered and sold during 1964 (Douglas 1965). However, cascara usually occurs as only a minor component of hardwood stands, and killing the trees when stripping the bark probably serves only as a thinning process. The vacated space in the stand is soon occupied by residual species or sprouts.

There appears to be no research in progress designed to develop additional markets for greenery, crude drugs, or other special forest products. It is conceivable that biochemical studies of shrubs, herbs, and other minor vegetation in Pacific Northwest forests might result in discovery of other plants that could be harvested for crude drugs. It is also possible that large-stemmed shrubs and weed trees could provide raw material for hardwood charcoal, woodpulp, or similar products. However, it seems highly unlikely that this type of research will be increased in the near future, while large volumes of more readily usable logging slash are being burned each year in new cuttings.

Puckerbrush pulping studies.--In Maine, weed trees and shrubs called "puckerbrush" were studied to determine their potential as a source of fiber for the paper industry (Chase et al. 1971, Gauvin 1972). Tests, with and without bark, were conducted on stemwood, branches, roots, and stumps of grey birch, red maple, pin cherry, aspen, alder, and willow. The raw material was pulped by the sulfate process. Yields of unbleached pulp ranged from a low of 37 percent for alder to a high of 47 percent for red maple. Stemwood without bark produced the highest yield of various mixtures of raw material. The authors concluded that at least four species (gray birch, red maple, pin cherry, and aspen) can be pulped by the sulfate process to produce a pulp equal to that of standard commercial pulps. Bark increased difficulty of bleaching, but an overall yield of 30 to 35 percent of bleached pulp can be produced from these species.

In the Pacific Northwest, red alder and other undesirable hardwoods have long been used as a small percentage of raw material in the paper industry. However, such species have not been used as much as they could be due to the availability of large amounts of more desirable and more easily processed coniferous pulp species. Utilization of hardwoods for pulp probably will increase in the future as supplies of more desirable species are depleted and technological advances provide improved processing methods for species now considered brush and weed trees. In type conversion projects, harvesting and sale of hardwoods could appreciably reduce amounts of residue from those species.

A relatively recent development has been Menasha Corporation's use of tanoak chips in preference to red alder for pulp in southwestern Oregon. Longer fiber length of tanoak allows more rapid operation of Fourdrinier machines and increased production.

ECOLOGICAL RESEARCH

Current ecological studies are mainly designed to obtain basic information concerning reproduction, growth, and development of native shrubs and weed trees. Fire is an important environmental factor in the ecology of many brush species, and repeated fires have been responsible for creating large, semipermanent brushfields on Pacific Northwest forest lands (Gratkowski 1967). Many brush species are able to survive wildfires or prescribed burning by sprouting from burls, roots, or root crowns (Mueggler 1965, Gratkowski and Philbrick 1965). In contrast, most conifers do not resprout, and repeated fires decimate and then eliminate conifers from a site, leaving a cover of fire resistant brush species to occupy the area. Some shrubs also produce long-lived seeds that evidently remain dormant but viable in forest soil for years until induced to germinate by heat from wildfires or prescribed burning (Quick 1959, Gratkowski 1961b, 1962). A better understanding of such relationships may provide a sound basis for modification of silvicultural practices to minimize acreage occupied by brush species and reduce forest residues in the future.

Other studies have shown that growth of young conifers can be seriously reduced by overstories of brush or weed trees. Snowbrush and red alder have been found to reduce growth of small conifers by more than 50 percent (Zavitkovski and Newton 1967). Varnishleaf ceanothus also drastically reduced growth of young Douglas-firs beneath the brush canopy (Lauterbach 1967, Gratkowski 1967, Gratkowski and Lauterbach 1974). An improved knowledge of interrelationships between conifers and brush species may aid in reducing future volumes of forest residue by indicating the minimum number of species to be controlled when releasing trees from brush competition.

FUTURE RESEARCH AND DEVELOPMENT

Much research and development are needed to provide silviculturists with adequate knowledge and effective tools for brushfield reclamation and type conversion in the Pacific Northwest. Such research can be classified into five categories: (1) mechanical site preparation, (2) chemical brush control, (3) prescribed burning, (4) ecological studies, and (5) utilization.

MECHANICAL SITE PREPARATION

1. A special need exists for mechanical eradication and scarification equipment that can operate effectively and economically on steep slopes in mountainous terrain. Prepared sites should be cleared enough to allow easy planting, and vegetative cover must be reduced to a degree that will assure successful establishment of planted conifers. Surface soil, however, should not be denuded or tilled or channeled to a degree that will result in serious erosion during heavy winter rains.

2. Heavy, self-propelled shredders or choppers that can operate on fairly steep terrain would also be useful. Again, the treated sites should be easily plantable. It would be especially desirable if such equipment would not only cut down brush and small weed trees but shred and break up the residue into a mulch that could be deposited on the site to add to soil fertility and moisture retention. In addition, mulching would eliminate the problem of residue disposal and could reduce new germination and resprouting of competitive vegetation. If such equipment can also operate on steep slopes, it could conceivably be used to shred piled and windrowed brush on sites cleared with other equipment.

3. Also needed are self-propelled cutters, choppers, or other equipment to clear roadside brush rapidly and with a minimum of expensive manual labor. Such equipment should be designed to clear vegetation to 10 or 15 feet (3 or 4.6 m) from the road edge on the steep cuts and fills characteristic of most forest roads. Such equipment should shred residues and leave the treated area with an esthetically acceptable appearance.

CHEMICAL BRUSH CONTROL

Several types of new herbicides and application equipment would be useful in treating brush and hardwoods and disposing of plant residues during site preparation. Any new herbicides must not only be effective; they should also be relatively inexpensive, persist for only a short time after controlling undesirable vegetation, and have little or no adverse effects on other life forms or the environment. Among the types of chemicals and equipment needed are:

1. New herbicides that will control species resistant to chemicals now available and to replace those discarded because they were environmentally unacceptable. Broad-spectrum herbicides are needed for site preparation. And additiona'l selective chemicals are needed to control undesirable species without damaging young conifers or other useful vegetation.

2. Safe, easy-to-handle desiccants that can quickly kill all aerial parts of a broad spectrum of brush species and allow the residues to be burned a month or two after application. Such chemicals also must not produce undesirable pyrolysis products.

3. Aerial spray equipment or easily used additives that will provide good control of droplet size, minimize spray drift, and insure accurate placement

of spray on the target area. Additives or sprays that the pilot can see on the vegetation would be useful in insuring complete coverage during aerial application. Associated research is also needed to determine optimum droplet size for proper spray coverage and maximum control of shrubs and weed trees.

4. Chemical or biological agents that can be sprayed on dead brush and weed tree residues to speed their decomposition. Such materials also must be without undesirable effects on live plants, other forms of life, or on the environment. They should remain in the treated area, not leach or wash into streams or adjacent. areas, and not persist long after accomplishing their purpose.

   Note: Agricultural scientists have been investigating enzymes of soft-rot pathogens that destroy pectin in cell walls of plant tissues (Hankin 1972). Their work may provide a lead to comparable enzymes for woody plants. Degradation of mulched or shredded residues should be especially feasible, if such enzymes can be isolated.

PRESCRIBED BURNING EQUIPMENT AND TECHNIQUES

Effort in this field can probably be limited to adapting new or previously developed materials and techniques devised for slash disposal. Electrical ignition techniques and flammable gels seem especially promising to increase safety and control ignition in burning chemically desiccated brushfields. Meteorological studies for smoke dispersal should also prove applicable.

Burning broad expanses of uniformly low dense brush, especially chaparral, seems especially favorable for production of fire whirls. Fire whirls easily cross firelines and make fire control difficult. Ignition techniques minimizing this tendency would add to safety and make prescribed burning more acceptable to many foresters.

ECOLOGICAL RESEARCH

Very few ecological studies of Pacific Northwest shrubs and weed trees have been conducted in the past. However, a sound knowledge of the ecology of native shrubs and weed trees and their interaction with coniferous trees is necessary for proper silvicultural management of shrubs and other competitive vegetation. Such knowledge would allow foresters to remove only those species needed to insure successful reforestation and acceptable growth rates in established conifers.

A better understanding of the ecology of native shrubs and hardwoods may also indicate practicable changes in harvesting methods that will create habitats favorable for regeneration of conifers but unfavorable for weed species. This, in turn, would reduce future acreage lost to brush and weed trees, reduce the need for expensive, laborious, and time-consuming reclamation treatments, and minimize amounts of residues that must be disposed of in brush control and type conversion operations in the future.

It is also entirely possible that ecological research may reveal previously unsuspected favorable effects of many species on the forest environment. Study of such interactions has been almost completely neglected in the past.

Studies of environmental effects of brush control and site preparation treatments also must be increased. Studies should not be limited to microclimatic and other physical factors of the environment. All changes in the ecosystem must be detected and measured if foresters are to insure maximum benefits with minimum adverse effects from vegetation management and site preparation. Such information will also provide a better understanding of the effects on logging, slash disposal, thinning and other forest management techniques as well.

Undoubtedly, increased ecological knowledge will also reveal that many sites are more suitable for production of hardwoods than conifers. Hardwoods considered especially promising include red alder, tanoak, California laurel, bigleaf maple, Pacific madrone, and golden chinkapin. Alder, tanoak, and bigleaf maple trees on many sites have excellent form and attain a size that should yield sawtimber useful for furniture and milled products. Genetic research to detect and develop the best strains of hardwoods could lead to increased utilization and reduced residues from such species.

UTILIZATION RESEARCH

Research is urgently needed to develop new uses and improved technology for utilization of hardwoods such as red alder, bigleaf maple, tanoak, and chinkapin. Availability of great volumes of conifer timber in larger trees has overshadowed this need in the past so that it has been almost completely neglected. However, considerable volumes of hardwoods are available. Rapid depletion of available old-growth conifer sawtimber makes it imperative that we now attempt to develop the technology that will allow us to use these hardwoods to supplement our softwood resources.

Increased utilization would also provide funds to help pay for converting these sites to production of conifers, minimize wasteful disposal of usable material, and reduce disposal costs. In fact, development of suitable technology for utilization of hardwoods may show that some species are entirely acceptable and desirable on large acreages of Pacific Northwest forest land. This could appreciably reduce residues to be disposed of as an expense of forest management. With species such as red alder, it would also simplify and reduce costs of forest regeneration.

Utilization research that seems desirable includes:

1. Development of processing techniques and equipment to increase production of pulp from alder and other hardwoods at reasonable cost.

2. Drying schedules and processing equipment to produce useful lumber from our smaller hardwoods. Such lumber might be further processed and manufactured into hardwood furniture or other milled products, thus adding to diversification of wood-using industries in the Northwest.

3. Biochemical studies of hardwoods and brush species may reveal additional special products and crude drugs that might further increase utilization of these "weed species" and further supplement the regional economy.

4. Special studies of small-stemmed brush species to determine whether shrubby vegetation can be utilized in production of usable pulp, mulches, packing materials, or other products. This field has been almost completely neglected.

These are but a few of the many types of studies that can be suggested. Favorable results from any of these, however, could serve to appreciably reduce wasteful disposition of potentially useful resources and save funds that can be better used in type conversion, brushfield reclamation, or improving growth of established conifers'.

SUMMARY

Between 4.4 and 6.0 million acres (1.8 and 2.4 million ha) of commercial forest land in the Pacific Northwest have been occupied by native shrubs and undesirable hardwoods. These lands require reclamation and reforestation or type conversion if they are to attain their productive potential. Reforestation, however, will not be easy; the shrubs and hardwoods include a great variety of herb, shrub, and tree species, many different plant communities, and much disparity in age and composition. Furthermore, they are distributed throughout numerous forest types on sites with a wide range of soil types, topographic, and climatic conditions.

Effective reclamation and type-conversion methods have included mechanical scarification and eradication, prescribed burning, and application of herbicides. Most sites, however, require a planned program involving combinations of methods to allow successful establishment of conifers and to insure dominance of the young trees over germinating, resprouting, and invading competitive vegetation.

Reclamation and type-conversion operations in Oregon and Washington can be expected to produce almost 240 million tons (218 million metric tons) of forest residue that must either be disposed of, concentrated, or accepted as an additional fire hazard for many years while it decomposes on the site. It seems reasonable, however, to expect that at least 150 to 200 million tons (136 to 181 million metric tons) will have to be eliminated by prescribed burning or other methods to reduce the fire hazard and prepare sites for reforestation. Silvicultural treatments, reclamation of areas previously planted with offsite stock, and thinning and weeding with silvicides could add appreciable volumes of residue. All such material must be considered in any appraisal of forest residue problems.

LIST OF PLANTS"

Scientific name	Common name
Acer circinatum	vine maple
Acer glabrum	Rocky Mountain maple
Acer macrophyllum	bigleaf maple
Acer rubrum	red maple
AZnus sp.	alder
AZnus rubra	red alder
Amelanchier spp.	serviceberry
Arbutus menziesii	Pacific madrone
Arctostaphylos spp.	manzanita
Arctostaphylos patula	greenleaf manzanita
Betula populifolia	gray birch
Castanopsis chrysophylla	golden chinkapin
Castanopsis sempervirens	Sierra chinkapin
Ceanothus spp.	ceanothus
Ceanothus integerrimus	deerbrush ceanothus
Ceanothus sanguineus	redstem ceanothus
Ceanothus velutinus	snowbrush ceanothus
Ceanothus velutinus var. *Zaevigatus*	varnishleaf ceanothus
Cercocarpus spp.	mountain-mahogany
Corylus cornuta var. *californica*	hazel, California.
Gaultheria shallon	salal
Lithocarpus densiflorus	tanoak
Lithocarpus densiflora var. *echinoides*	shrub tanoak
Menziesia glabella	smooth menziesia
Physocarpus malvaceous	mallow-leaved ninebark
Pinus ponderosa	ponderosa pine
Populus tremuloides	quaking aspen
Prunus spp.	cherry
Prunus emarginata	bitter cherry
Prunus pensylvanica	pin cherry
Pseudotsuga menziesii	Douglas-fir
Quercus chrysolepis	canyon live oak
Rhamnus purshiana	cascara buckthorn
Ribes spp.	currant
Rubus parviflorus	thimbleberry
Rubus spectabiZis	salmonberry
Salix spp.	willow
Sambucus spp.	elderberry
Umbellularia californica	California-laurel
Vaccinium spp.	huckleberry
Vaccinium ovatwn	huckleberry, evergreen

6/ Scientific and common names are those given in Agriculture Handbook No. 41, "Check List of Native and Naturalized Trees of the United States" (Little 1953). Those not in that reference are either from "An Illustrated Flora of the Pacific States: Washington, Oregon, and California" (Abrams 1955) or "An Illustrated Manual of California Shrubs" (McMinn 1951).

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REGENERATION AND GROWTH OF COASTAL DOUGLAS-FIR

Richard E. Miller, Richard L. Williamson, and Roy R. Silen

ABSTRACT

Environmental requirements for regenerating coastal Douglas-fir are described. The effects of forest residues and various residue treatments on natural regeneration and growth are discussed; in general, Zack of residue treatment favors regeneration of species more shade-tolerant than Douglas-fir. Residues left after harvest of old-growth stands are the most typical and most costly to eliminate especially where economics do not permit a high level of utiZization. Some of these residues have potential value for wood products or for soil humus and nutrients essential to soiZ productivity; however, residues can also be fire hazards or obstacles to other forest management objectives. Residues and their treatment affect the effort needed for regenerating, tending, and protecting the forest--timber yields as well as water, recreation, and wildlife are influenced. A detailed examination of conditions at each Zocation should routinely precede the slash treatment decision. In most situations, conservation of small branches, twigs, and needles is important to site productivity, particularly in managing immature or easily erodible soils. Information is presented to help the Zand manager assess the conflicting values of forest residues and determine the best treatment for specific site conditions.

Keywords: *Pseudotsuga menziesii*--site preparation, natural regeneration, soil productivity, tree growth, clearcutting, fire effects.

INTRODUCTION

All organic matter of the forest eventually falls to the forest floor as a result of natural stand development, catastrophic events, or man's activities. In commercially managed forests, man harvests whatever can be utilized for wood products; the remaining material is termed forest residue. Under natural conditions, forest residues are destroyed by wildfire or gradually mineralized or modified to humus and incorporated into the mineral soil.

Currently, excessive accumulations of residues remaining after harvest of old-growth stands are our most pressing residue problem in the Pacific Northwest.

Some of these residues have potential value for wood products or for soil humus and nutrients essential to soil fertility; however, if residues are left untreated, they can also be fire hazards or obstacles to other forest management objectives. For example, species composition, adequacy, and timing of natural regeneration are strongly influenced by the amount and distribution of residues or by the method used to reduce the hazard of wildfire. Timber harvest or accompanying residue treatment can affect the short-term growth and long-term productivity of Douglas-fir forests, as well as watershed and recreational values of the forest. Moreover, the practical effects of these operations depend on stand and site conditions; removal or redistribution of logging slash and the organic accumulation overlying mineral soil can be disastrous at some sites and of little long-term significance on others. Therefore, for maximum benefit:cost ratios from managing commercial Douglas-fir forests, the interrelations of individual management operations should be known and coordinated in planning and executing timber harvests, residue treatment, and subsequent regeneration and cultural practices.

DESCRIPTION OF FOREST TYPE, ENVIRONMENT, AND SILVICAL CHARACTERISTICS

Coastal Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* (hereafter called Douglas-fir), is the major tree species in one of the world's most productive forest types. The coastal variety is restricted to areas west of the Coast Range in British Columbia, west of the Cascade Range Crest in Oregon and Washington, west of the Sierra Nevada Range in northern California, and western Nevada. The Douglas-fir type currently covers approximately 11.7 million acres (4.7 million ha) in western Washington and Oregon.[1/] It represents about 47 percent of the commercial forest land and an estimated timber volume of approximately 352 billion board feet (International 1/4-inch rule) in that area (Wall 1969).

Forest Type and Environment

Coastal Douglas-fir is usually a subclimax component in the *Tsuga heterophylla* Zone (Franklin and Dyrhess 1969). This zone is characterized by a moist, mild maritime climate with dry summers, although there is much variation from differences in latitude, elevation, and location relative to mountains. Almost pure, even-aged natural stands of coastal Douglas-fir commonly evolved after wildfires or clearcut logging operations and slash burning. The principal associates of Douglas-fir are western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar (*Thuja plicata* Donn). Although Douglas-fir is a major species south of the *Tsuga heterophylla* Zone, our discussion will be limited to the Douglas-fir forests north of the divide between the North and South Umpqua Rivers and north of the Klamath Mountains in southern Oregon.

Soils supporting the Douglas-fir type vary widely in physical and chemical characteristics resulting in various amounts and rates of organic matter

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1/ Personal correspondence with Donald R. Gedney, Pacific Worthwest Forest and Range Experiment Station, Portland, Oregon, December 1973.

decomposition (Forest Soils Committee of the Douglas-fir Region 1957, Franklin and Dyrness 1969, Moore and Norris 1974). Regional soils also vary in susceptibility to erosional and productivity losses which are likely to follow severe disturbance of protective vegetation and the forest floor (Swanston and Dyrness 1973).

Silvical Characteristics and Microsite Requirements

To regenerate and grow Douglas-fir effectively, one should consider its requirements for and tolerances of moisture, temperature, light, and nutrients, and how these factors are affected by residues and residue treatment.

Coastal Douglas-fir is moderate in its soil moisture requirements, tolerating neither high water tables as do western redcedar and red alder (*Alnus rubra* Bong.) (Minore 1971), nor excessively droughty conditions as do ponderosa pine (*Pinus ponderosa* Laws.) and black oak (*Quercus kelloggii* Newbr.) (Waring 1969). Adequate soil moisture is particularly critical for seed germination and seedling survival. The amount and rate of movement of soil moisture to germinating seed or seedling roots are largely determined by soil characteristics and the amount of competing vegetation. Subsequent water use by the plant, however, depends on climatic stress and the plant's response to it. In the Douglas-fir region, warm, dry summers create large evapo-transpirational stress; relative to lodgepole pine (*Pinus eontorta* Dougl.) and ponderosa pine, Douglas-fir seedlings show less control of the amount of water lost to this stress. For example, at a soil water tension of -10 atmospheres, Douglas-fir seedlings continue to transpire about 32 percent of maximum rates compared with 9 percent for the pines (Lopushinsky and Klock 1974).

Extremes in air and soil temperatures have adverse effects on seedling survival and growth. High temperatures develop at the air-soil interface exposed to direct sunlight; sufficiently long exposure of seedlings to soil surface temperatures over 125° F may cause heat lesions upon the stems of newly germinated seedlings and subsequent death. Hence, intermittent shade and seed bed materials which conduct heat away from the seed bed surface are important in the ability of seedlings to survive high temperatures (Silen 1960). Soil surface temperatures above 138° F are usually lethal. Such temperatures are common on southerly slopes in the Oregon Cascades but also occur on exposed northerly slopes (Silen 1960, Hallin 1968b). Although first-year Douglas-fir seedlings gradually develop increased resistance to high temperatures (Keijzer and Hermann 1966), seedlings escaping or surviving high soil surface temperatures can die from prolonged drought which causes mortality losses throughout the Douglas-fir type (Isaac 1938).

Below-freezing temperatures are equally hazardous to young seedlings. Frost heaving of 1- to 2-year-old natural seedlings and freshly planted seedlings can be expected if temperatures drop below freezing and the surface soil is bare and moist. Frosts nip succulent new foliage of young seedlings. On established trees, foliage can be injured with subsequent loss of tree growth when very cold air temperatures occur (Reukema 1964b).

Douglas-fir seedlings have high requirements for nutrients compared with associated conifers (Walker et al. 1972). Yet, fertilization under field conditions generally fails to improve survival of artificially seeded[2] or planted

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2/ Unpublished data on file at Forestry Sciences Laboratory, Olympia, Washington.

Douglas-fir (Austin and Strand 1960, Rothacher and Franklin 1964), mostly because fertilization increases the growth of other vegetation competing for moisture. Nutrient tolerances or requirements probably increase with tree age; for example, light to moderate dosages of fertilizer which increased mortality of newly germinated seeds or young seedlings also increased growth in young pole-size trees (see footnote 2).

Only under very heavy slash or vegetative cover is light insufficient for survival and growth of Douglas-fir seedlings. Minimum requirement for normal growth of seedlings under field situations is about 50 percent of full sunlight (Isaac 1943); however, light requirements of Douglas-fir evidently increase with increasing moisture stress (Atzet and Waring 1970). This may explain why Strothman ([Strothmann] 1972) observed that shade did not improve survival of planted Douglas-fir in northern California and that 25-percent shade reduced seedling growth. There has been considerable investigation of light requirements of Douglas-fir seedlings in favorable growth chamber or nursery environments (Krueger and Ferrell 1965, Walker et al. 1972); however, extrapolation of these results to field conditions is uncertain. Thus, light-to-moderate shading of seedlings by residues or residual trees probably permits adequate light for normal survival and growth as well as protects from temperature extremes.

The capacity of microsites for providing Douglas-fir seed and seedlings with adequate moisture, temperature, light, and nutrients is markedly affected by forest residues and residue treatments. Residue treatment directly affects the amount and distribution of various kinds of seed beds, aboveground residues, and residual vegetation; subsequent plant succession and wildlife depredations are indirectly affected.

Mineral soil is the best seed bed for regenerating Douglas-fir from seed. Mineral soil surfaces are usually cooler with less extremes of temperature than organic matter seed beds (Anonymous 1929, Silen 1960, Hermann and Chilcote 1965, Fowler 1974). Mineral soil surfaces usually provide less competition from residual vegetation. In contrast, organic seed beds have insulating properties which delay the transfer of heat energy to and from the underlying soil, thus raising surface temperature during the day (Silen 1960) and depressing it at night (Silen 1960, Fowler 1974). Moreover, organic seed beds become excessively dry under exposed conditions. Although Douglas-fir seed germinates under a wide variety of conditions (Isaac 1943, Tappeiner 1966), rate and percentage of germination are affected by seed bed type (Hermann and Chilcote 1965).

Seed bed surface temperatures and moisture conditions are less critical for planted seedlings than for natural seedlings. The thicker bark of older, planted seedlings is more resistant to high soil surface temperatures and their roots are planted deep into mineral soil where moisture conditions are generally more favorable than in the surface soil. Under extreme conditions (steep south slopes with shallow soil, for example) even planted seedlings need protection from excessive surface temperatures and soil moisture stress. See also Edgren and Stein (1974).

The net effect on Douglas-fir regeneration of vegetational communities which develop on clearcuts is extremely variable and depends largely on relative rates of development between Douglas-fir seedlings and competing vegetation and the type of vegetation. For initial survival in most situations, recently germinated Douglas-fir seedlings need shade (Isaac 1943); however, moderate to heavy shading on seed beds can increase losses from damping-off fungi and clipping by white-footed deer mice *(Peromyscus maniculatus)* (Hermann and Chilcote 1965). Over a 6-year period at his study site in southwestern Washington, Isaac (1943) found that first-year survival averaged 7, 21, and 57 percent, respectively, with no shade, medium shade, and dense shade (logging debris and brush). Subsequent survival through 5 years was also improved by shade, although height growth was gradually reduced when the shade was provided by vegetation.

Vegetation can provide too much shade and competition for moisture. For example, Hallin (1968a) found that soil moisture at the 6-inch (15-cm) depth in late summer in a southwestern Oregon clearcut was at -15 to -25 atmospheres tension under 2-year-old herbaceous vegetation compared with 2 to 8 atmospheres where the vegetation was removed. Isaac (1943) concluded that species which occupy ground as well as crown space are more serious competitors than those which occur in clumps and leave growing space for seedlings below and between these clumps. Both Isaac (1943) and Dyrness (1965) concluded that invading herbaceous species were generally more competitive to Douglas-fir seedlings than residual shrub species. Besides moderating microclimate, some shrub species improve seedling survival growth by providing mechanical protection against browsing (Gratkowski 1967).

After initial survival, Douglas-fir needs to maintain a dominant position among its competitors. Investigations of snowbrush and varnishleaf ceanothus, two varieties of *ceanothus velutinus* which are promoted by slash burning, illustrate this point. Zavitkovski et al. (1969) concluded that snowbrush is eventually suppressed by conifers, but the period of dominance by snowbrush probably determines species composition of the succeeding conifer stand. If snowbrush remains dominant for more than 15 years, then only tolerant species, especially hemlock, can succeed it naturally. Douglas-fir and noble fir *(Abies procera* Rehd.), planted or natural, can be successors providing they become established at the same time as snowbrush. Similar results were reported in southwest Oregon for varnishleaf ceanothus (Gratkowski 1967).

FOREST RESIDUES

In unmanaged Douglas-fir forests, accumulation of residue typically starts after wildfire. As snags of the old, fire-killed stand break and fall, rotten wood accumulates and gradually decomposes. As the new stand grows through sapling, pole, and saw-log stages, it provides additional woody material from suppression and other losses. Most of this material is sapwood with little resistance to decay; and since the forest environment is usually well shaded, the forest reaches its most residue-free and fire resistant stage. As the new stand reaches maturity, mortality and live breakage have higher portions of heartwood which decay slowly in the moist conditions of the forest. Finally, accumulated wood on the forest floor of the unmanaged overmature or old-growth stand becomes so great that a catastrophic fire eventually occurs to start the cycle anew.

In harvesting old-growth stands, man interrupts this natural cycle and substitutes harvest for catastrophic fire. Because of the excessive amounts of residual organic matter of the forest floor and that contained in unmerchantable tree crowns and boles, these harvests create local fire hazards; these hazards remain until much of the residue gradually decomposes, burns through natural or accidental man-caused fire, or is purposefully treated by burning or mechanical means.

In managed, young-growth Douglas-fir stands, few residues persist because the amount of natural residue is small and includes only a small proportion of decay-resistant wood. Intermediate and final harvests of these young-growth stands produce less slash than old-growth harvest, because of reduced defect and felling breakage. Thus, increased utilization of total wood production will help minimize the future residue problem.

Types and Amounts of Residues

Natural residue situations.--As one of the world's most productive forest types, coastal Douglas-fir produces large quantities of forest residues. Average annual litter fall (needles and twigs) in young Douglas-fir stands is approximately 1 ton per acre (2.24 metric tons per ha); lesser amounts fall in thinned stands (Reukema 1964a). Litter fall in old-growth stands of similar site quality is about the same; however, larger limbs, bark, and understory hardwoods contribute an additional 1 ton per acre (2.24 metric tons per ha) per year (Abee and Lavender 1972). Normal and catastrophic tree mortality contribute additional amounts.

With the most favorable soil and climatic conditions and least decay-resistant plant residues, there is rapid soil biological activity and thus rapid decomposition of litter fall or incorporation into the soil. Only a thin layer of organic residues, the forest floor,[3/] accumulates above the soil. This is the so-called "mull" forest floor type, which is readily observed in red alder and fast-growing Douglas-fir stands. As macroclimate or microclimate becomes cooler or drier, soils less fertile, or plant residues more resistant, soil biological activity is reduced and increasing amounts of residues accumulate. In extreme situations, the so-called "mor" or "raw humus" (Hoover and Lunt 1952) form is observed; this forest humus type indicates an undesirably low rate of organic matter and nutrient cycling. Under these conditions, an average of 70 tons (150 metric tons per ha) of organic matter and 1,800 pounds of nitrogen per acre (2,017 kg per ha) accumulated on the forest floor in nine old-growth stands in western Washington (Gessel and Balci 1963). In the majority of Douglas-fir stands, however, an intermediate, "duff mull" humus type is present. This type can have quantities of organic matter overlying mineral soil that are nearly as deep as in the mor type (Gessel and Balci 1963); however, there is an incorporation of organic matter in the upper soil so that an A_1 horizon is present as in the mull type.

Man-related residue *situations*.--Through his final or intermediate harvests, cultural practices, or road construction, man periodically increases the rate of organic deposition. Within 10 to 12 years, needles and twigs of Douglas-fir slash usually decompose on joist sites, but some foliage and much twig material remain on very dry sites (Childs 1939). A study (Wagener and Offord 1972) in the mixed conifer type of northern California over a 34-year period suggested that high summer temperatures and low summer and fall precipitation were major factors affecting slash decay organisms. Residue treatment is particularly important on an estimated 100,000 acres (40,000 ha) of old-growth coastal Douglas-fir harvested annually; considerably less important on a greater number of acres of young growth. Old-growth logging slash often exceeds 150 tons per

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3/ Terminology used in this paper corresponds to that of the Soil Science Society of America Committee on Terminology (1965).

acre (335 metric tons per ha), and residues from harvest of 80- to 150-year-old Douglas-fir are likely to be less than half this amount (Dell and Ward 1971). Although the acreage harvested annually in mature young growth is increasing steadily, cutting in old growth is expected to continue for several decades.

Characteristics of Forest Residues

Residues vary in quality as well as quantity. Type and size of residue are significant; small size residues initially are a greater fire hazard (Morris 1970), but they contribute more nutrients to the soil than do tree boles (Moore and Norris 1974):

	Needles	Branches	Boles
Weight per acre	Minimum	Moderate	Maximum
Fire hazard:			
Rate of spread	Maximum	Moderate	Minimum
Resistance to control	Minimum	Moderate	Maximum
Nutrients per ton	Maximum	Moderate	Minimum
Rate of conversion:			
To minerals	Maximum	Moderate	Minimum
To humus	Maximum	Moderate	Minimum

Need and Methods for Residue Treatment

At present, residues from clearcutting of old-growth timber are the most difficult to treat in coastal Douglas-fir forests. The increasing use of shelter-wood harvesting and regenerating systems, particularly in southwestern Oregon, creates lower fire hazard and intensity than clearcutting because slash is spaced out between two or three cuts at least 5 years apart. Moreover, under the protective canopy, slash does not dry so rapidly as in the open (Fahnestock 1960) and, therefore, decays more rapidly (Aho 1974). If needed, slash can still be disposed of by burning or other means, although these measures are usually more costly to apply within a partially cut than in a completely cut stand. Use of shelterwood systems probably will increase as young-growth forests make up a higher proportion of the total harvest.

With all harvesting systems, the land manager can initially minimize residues by felling carefully to reduce breakage and thus increase utilization of the tree bole. Some of the unmerchantable tree boles are decayed, shattered, or broken beyond intensive utilization; however, it has been estimated that about 50 percent of the volume in unmerchantable boles meet current utility log standards and could produce about one-half the raw material requirements of regional pulp, paper, and particle board industries (Howard 1971). Increased stumpage prices and improved harvesting and manufacturing practices will provide additional incentives for better utilization. Thus, there is considerable opportunity for increasing usable yields per acre and for reducing residue and thus costs of fire protection.

Although utilization of economically marginal or submarginal logs increases harvesting costs, it reduces cost of residue treatment and site preparation for future silvicultural operations. In 1970, the U.S. Forest Service in the Pacific

Northwest Region began requiring that all logging residues exceeding specified minimum sizes be yarded to landings. Appraised stumpage prices were reduced to compensate the operator for the extra logging costs. Expectations were that some residues, after being yarded to landings, might have enough value to pay for loading and hauling them to manufacturing sites.[4/] However, transporting defective material to a mill may change the nature of the residue disposal problem. When decks of yarded cull material are not used, they may be burned or left as a concentrated, localized hazard.

Although numerous alternatives are available for treating residues, the manager's specific choice must depend on his management objectives and the specific site conditions, e.g., volume and arrangement of residue, steepness of slope, and stability of soil. His options include leaving residue to decompose naturally or burning it broadcast, in piles, or with mechanical help as in pits with a blower or in a portable bin. He may leave it unburned but treat it mechanically by chipping, crushing, or burying. He may windrow, pile, or move it into ravines or other depressions. More restrictive options include treating with fire retardants or decay-promoting chemicals or removing most residues from the site for use or disposal elsewhere.

RESIDUE TREATMENT AND DOUGLAS-FIR SILVICULTURE AND MANAGEMENT

The prudent forest manager considers his management objectives, the local residue situation (existing or pending), and the treatments most likely to help obtain these management objectives. Residues and residue treatments affect costs and benefits of forest management. If treatment is needed, then what are the costs and benefits of various options at a specific location? If residues are left untreated, the manager saves cost and contributes to soil productivity; to some degree, however, the manager thereby incurs a fire hazard and other obstacles to regeneration or stand access. Conversely, by treating residues, future fire protection and possible regeneration costs will be reduced. Although residue treatment reduces organic matter and disturbs soil, some of this can be offset by other treatments (for example, fertilizers or erosion control).

Common management objectives on lands designated for wood production, the major variables affecting them, and additional sources of information are:

Management objectives	Major variables	Additional compendium information
1. Minimize production costs (per acre and per unit of products removed)	1. Residue disposal	Martin and Brackebusch 1974
	2. Regeneration of desired species	Ruth 1974, Seidel 1974, Edgren and Stein 1974
	3. Stand accessibility	
	4. Protection	
	Fire	Martin and Brackebusch 1974
	Insects	Mitchell and Sartwell 1974
	Disease	Nelson and Harvey 1974
	5. Soil amendments	Moore and Norris 1974

4/ See Forest Service Manual 5750.3--5 Supplement R-6 65, April 1972, regarding YUM (yarding unutilized material).

Management objectives	Major variables	Additional compendium information
2. Maintain or improve soil productivity	1. Organic matter	Moore and Norris 1974
	2. Soil disturbance	Bollen 1974, Aho 1974
	3. Soil compaction	Rothacher and Lopushinsky 1974
3. Maximize compatibility with nontimber products	1. Water quality	Rothacher and Lopushinsky 1974
	2. Recreation	Wagar 1974
	3. Wildlife	Dimock 1974, Garrison and Smith 1974 Brown 1974

Soil is the basic resource of the land manager; maintaining or improving soil productivity should be a major management objective. Yet, harvesting Douglas-fir timber and treating residues inherently lead to some loss of soil productivity, so the land manager seeks to reduce these impacts by choosing methods which minimize the percentage of the area affected and the degree of disturbance to the mineral soil or to the vegetation and organic layer protecting it. Additionally, he can correct them through soil-improving practices. Except for catastrophic loss of soil mantle, changes in forest soil productivity are difficult to measure. Thus, general principles of soil management must frequently be accepted on the basis of intuition rather than evidence.

By minimizing disturbance on most forest soils, we maintain high infiltration rates and reduce surface runoff and thus potential for soil erosion. A concern for organic matter' losses and erosion is particularly important on certain soils and situations, including: (1) soils on steep slopes; (2) soils with low infiltration rates; and **(3)** soils developing from acidic parent materials such as granite, rhyolite, and some sediments in contrast to those from more basic parent materials such as basalt, andesite, and gabbro (Dyrness 1966, Swanston and, Dyrness 1973). Soil compaction is a disturbance of particular concern on fine textured soils, especially when these are wet; conversely, compaction is of little concern on gravelly or sandy soils.

More than ever before, the residue decision requires an evaluation of the compatibility of treatment options with water quality, recreation, and wildlife. The land manager must consider all his management objectives and possible trade offs. Although general guidelines will guide his planning, his decision will depend on the local situation. Where residues accumulate to unacceptable levels, choice of treatment should attempt to minimize the ratio between total treatment costs (including site degradation or remedial efforts) and treatment benefits.

EFFECTS OF UNTREATED FOREST RESIDUES

Amount and distribution of forest residues affect the cost of harvesting, regenerating, tending, and protecting the forest.

RESIDUES AND CONDITIONS FOR NATURAL REGENERATION

In clearcut harvests of Douglas-fir with no residue treatment after logging, from 94 to 65 percent of the area may remain relatively undisturbed (Swanston and Dyrness 1973). Minimal disturbance results when low volumes per acre are removed and yarding systems which primarily lift logs rather than drag them are used; e.g., skyline, balloon, or helicopter. If residues are left untreated and increased fire hazard is accepted for a period of time, then the costs of regenerating Douglas-fir may be substantially increased or decreased depending on the specific situation. If natural regeneration is the manager's objective, then the benefits of this no-treatment residue decision depend on (1) the presence and species of advance regeneration; (2) anticipated natural seed fall; (3) types, amounts, and distribution of seed bed surfaces and microclimates; (4) types of residual competing vegetation; and (5) likelihood of wildfire.

Untreated residues are usually poor seed bed materials for initial survival of Douglas-fir; the presence of excessive residues as deep forest floor or dense logging slash can preclude Douglas-fir natural regeneration (Bever 1954, Lavender et al. 1956). Presence of residues is of less concern if planted seedlings are used, although quantities of slash after harvest of old-growth stands usually inhibit planting operations (Edgren and Stein 1974). In part because of its effectiveness in improving accessibility for planting and other stand management practices, broadcast slash burning has been a standard practice in the Douglas-fir region.

A major benefit from slash is that it provides numerous patches of shade throughout cutover areas, thus moderating high and low surface temperatures (Silen 1960, Hallin 1968b, Fowler 1974) and reducing mortality from freeze, frost heave, heat lesion, and drought.

Shrubs or lesser vegetation remaining after logging might be considered forest residues and a factor in the treatment decision (Jemison and Lowden 1974). With some notable exceptions, residual vegetation--in contrast to invading species--is probably of little consequence in successfully regenerating Douglas-fir. Nontree species, present in the stand before logging, usually decline in vigor or increase their area occupancy very slowly after logging (Yerkes 1960, Dyrness 1965). Exceptions are established salmonberry (*Rubus spectabilis* Pursh) communities characteristic of open Douglas-fir and red alder stands of the Coast Ranges and swordfern (*Polystichum munitum* (Kaulf.) Presl.)--Oregon oxalis (*Oxalis oregana* Nutt. ex T. & G.) communities on moist sites in the western Cascades. These two communities commonly increase rapidly in vigor a'fter timber is clearcut. Invading species, including *Ceanothus* species, are usually more serious competitors for Douglas-fir seedlings (Dyrness 1965). Control of such living residue may be necessary to minimize competition and assure successful regeneration (Gratkowski 1974).

RESIDUES AND SOIL PRODUCTIVITY

Climate and soil are major factors of site productivity. Productivity of forest soils can be improved or degraded by man's activities, especially those affecting quantity, quality, and distribution of organic matter on or in the mineral soil. Since fine-textured residues are a principal source of soil humus and many nutrients needed for forest growth, a general guideline is: Minimize the loss of such materials from the site. This precaution is particularly important on immature soils which characteristically contain relatively small amounts of soil humus and nitrogen.

Because insufficient nitrogen characteristically limits growth of Douglas-fir forests in the Pacific Northwest, the loss, accumulation, and cycling of this element in and between vegetation, forest floor, and soil are particularly significant. In forest soils of western Washington and Oregon, the amount of nitrogen in the mineral soil ranges from about 1,800 to over 23,500 pounds per acre (2,000 to over 26,000 kg per ha) with lower amounts associated with coarse-textured, immature soils and higher amounts with fine-textured, residual soils (Gessel et al. 1972). Thus, in the absence of forest floor and vegetation, all nitrogen of the site is contained in the soil. As vegetation develops, nitrogen accumulates in the forest floor and stand so that the proportion in the soil may fall to 50 to 80 percent of the total, with lower percentages in immature soils. Although total organic matter production on coarse-textured or immature soils is relatively low, the low level of biological activity on such soils can result in a faster rate of forest floor accumulation than on deep, mature soils. Except for extremely hot fires, most soil nitrogen is safe from loss through forest management; however, management practices can redistribute soil N from specific microsites through mechanical disturbance or erosion or cause nitrogen to be less available for plant use by degrading the environment for soil micro-organisms (Bollen 1974).

Primarily due to variations in stand age and decomposition rate, nitrogen in the overlying forest floor varies in quantity and in proportion to the total supply. In coastal Douglas-fir forests, nitrogen in the overlying forest floor generally ranges from 90 to 1,800 pounds per acre (100 to 2,000 kg per ha) (Gessel et al. 1972). For example, in immature, pole-size stands, 90 to 270 pounds per acre (100 to 300 kg per ha) may be located in the forest floor; in old-growth stands, 1,250 to 1,800 pounds per acre (1,400 to 2,000 kg per ha) have been measured in duff-mull and mor humus types (Gessel et al. 1972). Nitrogen in the overlying forest floor is likely to be reduced or redistributed by residue treatments.

Nitrogen in the subordinate vegetation and the tree stand gradually accumulates, primarily through withdrawals from the nitrogen capital of the soil. Although amounts and distribution of nitrogen in mature and overmature stands of Douglas-fir are unknown (Gessel et al. 1972), total amounts of N in all aboveground vegetation are probably less than 1,000 pounds per acre (1,120 kg per ha), even in old-growth Douglas-fir of highest productivity. For example, Moore and Norris (1974) have estimated that 760 pounds per acre (852 kg per ha) might be contained in tree crowns and stems of a 400-year-old Douglas-fir stand on average site quality. A 36-year-old Douglas-fir plantation on an immature soil in Washington showed the following distribution of nitrogen (Dice 1970):

Component	Pounds N per acre	Percent of total
Forest	286	9.7
Subvegetation	5	.2
Forest floor	156	5.3
Soil	2,506	84.8
	2,953 (3,310 kg/ha)	100.0

From data on nitrogen transfer and accumulation at this site, Gessel et al. (1972) have estimated that by the time this stand is 200 years old, the soil will contain less than 50 percent of the total amount of N. Thus, more than 50 percent of the nitrogen capital will be vulnerable to loss or redistribution by wildfire or tree harvest and subsequent slash reduction or site preparation efforts. In contrast, sites with larger quantities and proportions of N in the soil are less vulnerable to reductions in site productivity through natural fires or man's forest activities.

RESIDUES AND MORTALITY LOSSES

Although conservation of certain forest residues is desirable, excessive accumulation may lead to mortality through fire (Martin and Brackebusch 1974), bark beetles (Johnson 1970, Mitchell and Sartwell 1974), or disease (Nelson and Harvey 1974). To the extent that mortality is unsalvaged or creates unused openings in the stand, it leads to reductions in usable yields and short-term productivity.

Residues from thinning operations in young-.growth stands can constitute a fire hazard for several years. The hazard gradually abates as needles fall, the slash compacts, and the canopy closes (Fahnestock 1960). Without treatment, these residues can increase the intensity of accidental ground fires so that serious damage or loss in the stand can occur.

In some cases, the amount of nitrogen available to residual trees may be temporarily reduced by organisms decaying residues (Cochran 1968); this could cause losses in growth but, in our opinion, is unlikely to cause mortality in Douglas-fir.

EFFECTS OF RESIDUE TREATMENTS

Although recognizing the impossibility of completely fireproofing his forest, the land manager frequently finds situations where combinations of factors clearly favor residue treatment. By appropriate choice of method of treatment, however, he can achieve optimum balance between his objectives--minimum production costs, maintenance of soil productivity, and maximum compatibility and benefits to water quality, recreation, and wildlife.

Treatment methods may be compared by the proportion of the total area that is affected and the degree to which: (1) organic matter on or below the soil surface is removed from or redistributed over the treated area--if organic matter has been consumed by fire, nitrogen, sulfur, and phosphorus are lost from the site to the atmosphere, but most other nutrient elements in the ash or unconsumed organic matter remain onsite; (2) mineral soil is physically disturbed--i.e., loosened, compacted, or mixed with organic matter; (3) existing vegetation or conditions for invading vegetation are affected--this vegetation can be a soil protector or a potential fire hazard, but also a potential competitor for seedlings and established trees; (4) residual seedlings or trees within or surrounding the treatment area would be directly affected.

Currently, there is little direct evidence of the effects of various methods of treating residues on soil productivity, regeneration, and growth of Douglas-fir. However, by knowing the effects of treatment on environmental factors, one can predict the effects of these changed factors--and thus treatment--on seedling or tree growth. For example, treatments which disturb mineral soil on steep slopes are likely to cause soil erosion and thus loss of productivity.

It is important to recognize, however, that residue treatment is only one activity in the harvesting operation that changes forest environment. Road construction and maintenance in steep terrain are major and recurring causes of soil disturbance and erosion (Swanston and Dyrness 1973, Rothacher and Lopushinsky 1974); however, assessing the effect of individual harvesting activities is difficult. Each successive harvesting activity contributes new disturbance or exposure of the mineral soil and masks the effect of the previous activity. For example, Dyrness (1972) reported that the limited amount of bare soil exposed after balloon yarding (6 percent, compared with that after skyline and high-lead yarding, 12 and 14 percent, respectively) permitted him to identify that most of the slightly disturbed area resulted from tree felling and yarding.

Some yarding or residue treatments cause more site disturbance than others, and the effects of treatment also vary from site to site. Critical variables include: size and amount of residue, steepness and irregularity of the terrain, and fragility of the soil. Consequently, generalities have limited application. For high quality of land management, analysis and prescription of treatment and equipment for each site and residue situation are necessary.

EFFECTS OF BROADCAST BURNING

Starting in the late 1930's, slash burning in the Douglas-fir type was investigated to determine its effects on fire hazard, natural and planted regeneration, secondary plant succession, and on physical, chemical, and biological properties of the soil. Much of this work has been summarized (Tarrant 1956, Dyrness 1966, Morris 1970). There is general agreement that, in return for reduction of fire hazard and elimination of physical barriers to planting and some potentially competitive vegetation, slash burning causes additional baring of mineral soil and losses of organic matter from the forest floor and mineral soil. However, the potentially harmful effects of slash burning on soil productivity were considered restricted to severely burned portions which were usually less than 10 percent of the total area. All investigators recognized that better utilization standards in harvesting old-growth timber and a greater proportion of harvests in young-growth timber would further reduce the need for or intensity of slash burning.

Hazard *reduction*.--Morris (1970) concluded that broadcast slash burning accomplishes its primary purpose of reducing wildfire hazard. From an extensive sampling in western Washington and Oregon, he estimated that slash burning greatly reduces probable rate of wildfire spread and resistance to control for

5 years, and significantly reduces rate of spread for 15 years. However, in areas where luxuriant growth of herbaceous vegetation provides an annual crop of dead fuel, burning offers a shorter period of reduced rate of spread. Thus, by burning slash during favorable weather and with adequate personnel using correct procedures, a manager can reduce danger of uncontrolled fires. But even during weather favorable for burning, a sudden change of wind or fuel moisture may spread fire beyond the slash area into surrounding timber. "Either leaving or burning slash entails risk." (Morris 1958, p. 43).

Severity ***and extent of burning.***--Broadcast burning after clearcutting old-growth Douglas-fir provides a mosaic in burning intensity and its effects (table 1). With few exceptions, the portion of the sampled unit which was severely burned (mineral soil exposed and changed in color--usually to reddish), was less than 10 percent; severe burning occurred in small, scattered patches, usually where some logs or stumps had produced prolonged intense heat.

Less intense fire can expose mineral soil without changing its color. Morris (1958, 1970) reported this moderate burn condition averaged 22 and 14 percent of the area on his plots in the western Cascades and coastal Oregon, respectively. Morris (1970) found exposed mineral soil on 50 percent of line transects on burned plots, but only 22 percent (presumably from logging) on nearby unburned plots. Thus, fire more than doubled the amount of exposed mineral soil, most of which was probably in the moderate burn category (table 1). Tarrant (1956) and Dyrness et al. (1957) evidently found so little of the moderate burn category in their respective study areas that they did not classify or record it. One likely explanation is that they sampled burned clearcuts to determine the extent of various severity classes for the entire unit, whereas Morris rejected candidate plots that were less than two-thirds blackened by a slash fire; thus, Morris probably overestimated severity of burning on the entire unit. There is little question that broadcast slash burning can expose additional mineral soil without severely affecting its color. It is unlikely, for example, when slash was broadcast burned on a skyline logged clearcut and the percent of bare mineral soil was increased from 12 to 55 (Mersereau and Dyrness 1972), that all mineral soil was severely burned. The question remains as to the extent to which moderate burning occurs and its effects on soil and subsequent vegetation.

Lightly burned and unburned portions combined averaged 72 to 94 percent of broadcast burned units (table 1). With light burning, fire consumed branches, twigs, needles, and logs less than 11 inches (28 cm) in diameter, and blackened or charred the forest floor without completely consuming it. Unburned areas include those in which logging removed potential fuel, as in skid trails.

The amount of additional mineral soil exposed by severe and moderate burning can have practical consequences in regeneration and soil erosion. Investigations have shown that broadcast burning increases the amount of mineral soil over that exposed by logging. The additional mineral soil has varied from slight (8-12 percent) to excessive (43 percent) which resulted in exposed mineral soil on more than half of the unit (table 2).

Burning ***temperatures*** *and* ***their effects***.--To the general statement, "the hotter the fire, the cleaner the burn," one can add: "and the more destructive of soil productivity"; this revised statement summarizes the conflict facing the land manager. With the objective of removing residues with minimal future

Table 1.--*Extent* of *bum by severity classes* from *broadcast slash burning in otd-growth Douglas-fir clearcuts*

Location	Clearcuts observed	Average severity of broadcast burn				Source
		Severe 1/	Moderate 2/	Light 3/	Unburned 4/	
	Number		- - - - - - *Percent* of *total area* - - - - - -			
Western Cascades	49	6	22	55	17	Morris 1970
Coastal strip, Oregon	9	.1	14	75	10	Morris 1970
Western Cascades	10	3	(5/)	47	47	Tarrant 1956
Western Cascades, Oregon	8	2	7	29	62	Silen 1960
Corvallis watershed	3	8	(5/)	44	48	Dyrness et al. 1957

1/ Severe burn--top layer of mineral soil exposed and changed in color, usually to reddish.

2/ Moderate burn--duff and other woody debris consumed but mineral soil under ash not changed in color.

3/ Light burn--duff and other woody debris partly burned, but not to mineral soil.

4/ Unburned--mineral soil, duff, or other woody debris.

5/ Not found or classified.

Table 2.--*Percent of mineral soil exposed after Zogging and after fire by yarding method*

Yarding method	Units examined	Mineral soil exposed			Source
		After logging	After fire	Increase by fire	
	Number	-----	*Percent*	-----	
Unspecified	58	1/22 [1]	50 [2]	28	Morris 1958
High lead	3	31 [3]	39	8	Dyrness et al. 1957
High lead	4	44	56	12	Silen 1960
Tractor	3	36	48	12	Silen 1960
High lead	1	12	55	43	Mersereau and Dyrness 1972

1/ An underestimate because plot selection avoided areas without slash such as catroads.

2/ An overestimate because sampling was restricted to well-burned plots.

3/ An underestimate; includes "disturbed, unburned" but not "disturbed, burned" category.

fire hazard and air pollution (Fritschen et al. 1970), he will attempt to create conditions for a rapid, hot burn. As he increases fire temperature, however, he increases his losses of fine-textured organic matter and the depth and degree to which he affects the mineral soil (table 3).

At low fire temperatures, vapors and gases flow from the organic matter, some of these gases contain hydrophobic .substances which condense on cooler surfaces within the soil and subsequently cause an undesirable water-repellency that lasts at least 5 to 10 years (DeBano and Rice 1973). Significant to our particular concern about the effects of residue treatments on immature soils is the observation in Western United States that coarse-textured soils become more water-repellent than soils of finer texture, possibly because there is less surface area to coat with hydrophobic substances (DeBano and Rice 1973).

When organic matter is consumed by burning, practically all its content of nitrogen (DeBell and Ralston 1970), sulfur (Allen 1964), and much phosphorus (Grier 1972) are lost as gases to the atmosphere. Nitrogen and other elements in unconsumed organic matter remain on the site along with ash from consumed

Table 3.--*Effects of burning temperature on organic matter and soil depth at which such temperatures were attained*

Maximum temperature[1]		Effects on organic matter[1]	Soil depth under	
°C	°F		Heavy slash[2]	Light slash[2]
			Inches	
100-200	212-424	Nondestructive distillation of volatile organic components	2+	2
200-300	424-636	Destructive distillation of up to 85 percent of organic matter; sound wood does not ignite; black ash or charcoal residue	½	½
300	636	Ignition of carbon residues	¼ - 1½	½ - 1
450-500	842-932	White ash residue	0	¼
		99 percent of organic matter removed if temperatures maintained at 500° C for ½ hour		

1/ Ralston and Hatchell (1971).
2/ Neal et al. (1965).

organic matter. Precipitation leaches these nutrients to the soil below and causes temporary increases in pH which can favor nitrate production (Moore and Norris 1974). If vegetation is still present, only insignificant amounts are leached from the rooting zone (Grier and Cole 1971, Fredriksen 1971).

On severely burned portions (usually less than 10 percent of the total area) of clearcut units, physical, chemical, and biological properties of soil are adversely affected (Isaac and Hopkins 1937, Tarrant 1956, Dyrness et al. 1957, Neal et al. 1965). These changes are likely to affect plant growth adversely. Moisture-holding capacity in the top few inches of mineral soil is reduced (Neal et al. 1965), with loss of some organic matter, nitrogen, sulfur, and phosphorus, and possible increases in available nitrogen, ash, and pH. When severe burning occurs, water-stable soil aggregates are reduced in number and size, presumably by losses of associated organic colloids (Dyrness et al. 1957). Clay and silt fractions decrease with corresponding increase in coarse fractions (Dyrness et al. 1957). Water in the clay lattice structure is evaporated so that expanding clay types (montmorillonitic) permanently lose their capacity to expand and contract; net effect is for clay aggregates to assume the moisture characteristics of sands and gravels (Ralston and Hatchell 1971).

Broadcast Burning and Natural Regeneration

Despite wide variations in its severity and extent, broadcast burning normally affects 40 to 90 percent of a clearcut unit (table 1). Most of the area is lightly burned where fire consumes branches, twigs, needles, and small logs and blackens the forest floor. Burning destroys or severely damages any advance regeneration (mostly species other than Douglas-fir) and destroys any new seedlings or seed from the most recent seed fall of Douglas-fir; burning subsequently affects fate of seeds falling on the burned area and the seedlings which develop from them.

Burning influences subsequent above- and below-ground microclimate (Fowler 1974) affecting both seed and seedlings of Douglas-fir directly, as well as indirectly through effects on associated fungi, plants, and animals. On charred or blackened forest floor, soil temperatures are increased (Isaac 1938, Neal et al. 1965); this can increase the amount and rate of seed germination (Hermann and Chilcote 1965). Where early spring frosts are a problem, earlier germination of Douglas-fir and a scarcity of protective overhead slash or vegetation, with consequent freezing, could reduce stocking. Conversely, stocking could be improved by earlier or greater germination in areas where heat and drought are major factors of seedling survival, because seedlings would be older and therefore more likely to tolerate environmental extremes (Keijzer and Hermann 1966) or more numerous so that sufficient seedlings survive the greater mortality from higher soil surface temperatures characteristic of burned seed beds (Isaac 1949, Silen 1960). For example, Hermann and Chilcote (1965) sowed equal numbers of Douglas-fir seeds on different seed bed materials placed on an unburned silt loam on a south aspect in the Coast Ranges of Oregon; despite greater postgermination losses, they found significantly greater first-year survival on charcoal (30 percent) and soil discolored from a hard burn (17 percent) compared with lightly burned soil, litter, nonburned soil, and sawdust (17 to 12 percent).

In general, less than 10 percent of clearcuts and burned units is severely burned so that all surface organic matter, including charcoal, is removed and the soil baked to a reddish color. Existing data (table 1) suggest that about three times more area is moderately burned. Changes in severely burned soil may adversely affect Douglas-fir regeneration, but our information is limited and frequently conflicting. Although existing seed and seedlings are destroyed, germination of subsequent seed is not affected (Tarrant 1954) or may be increased in rate and amount (Hermann and Chilcote 1965). Postgermination losses to heat damage are generally reduced where mineral soil is exposed. In greenhouse or laboratory tests, losses to damping-off fungi increase on severely burned soil, presumably because increases in soil pH promote growth of these organisms (Tarrant 1954). In a field study, however, Hermann and Chilcote (1965) noted that damping-off losses typically occurred where shade existed and presumably provided a moist environment at the soil surface for these fungi; such conditions are unlikely on severely burned areas because the seedlings would probably be resistant by the time shade from vegetation developed on severely burned spots. However, seedling losses to drought are likely where severe burning reduces moisture-holding capacity of soil.

Subsequent growth of surviving seedlings on severely burned soil has been measured at only a few locations. At two sites, growth of 1- and 2-year-old natural Douglas-fir seedlings was not inhibited (Tarrant and Wright 1955), although the proportion of mycorrhizal seedlings was reduced by severe burning (Wright and Tarrant 1958). These observations of young natural seedlings in severely burned microsites conflict with earlier, longer term observations on, survival and growth of planted Douglas-fir (Isaac and Hopkins 1937). They noted particularly low survival of seedlings planted in severely burned spots where several logs had been burned together. Survival of replacement seedlings increased annually up to the fifth year of replacement, when practically all survived. However, even in their 10th year, Douglas-fir seedlings in heavily burned soil were not as vigorous as those growing on lightly burned soil. Baker and Phelps (1969) also reported that 1-year-old Douglas-fir grown on burned soils were about half as tall as those grown on unburned soils. They collected undisturbed soil cores from two different soils and grew their seedlings under controlled conditions of temperature, light, humidity, and water. In short, additional direct evidence about the effects of burning on Douglas-fir is needed, especially on shallow or coarse-textured soils.

Competing and protecting vegetation is affected.--Secondary succession after clearcutting provides a luxuriant development of brush and herbaceous species which survive logging or invade clearcuts. With slash burning, however, other changes can occur on the 40 to 90 percent of the unit affected. Burning eliminates some species from the original forest and delays expansion of others capable of resprouting. These shrubs include salal *(Gaultheria shallon* Pursh), Oregon grape *(Berberis nervosa* Pursh), vine maple *(Acer circinatum* Pursh), and salmonberry *(Rubus spectabilis* Pursh) (Isaac 1943). Morris (1970) found that slash burning usually reduced shrub (brush) competition for several years and in the coastal strip of Oregon reduced the prevalence of salmonberry, a particularly strong competitor for Douglas-fir seedlings. However, at some sites in the southern Cascade Range, heat associated with slash burning stimulates germination of long-dormant seed from several shrub species not present in the stand at harvest. These included several species of manzanita *(Arctostaphylos* spp.), *Ceanothus* spp., and sumac (*Rhus* spp.) (Gratkowski 1967). Seed beds created by burning were quickly populated by herbaceous species with windblown seed, but total herbaceous growth was not significantly different from unburned areas (Morris 1958, 1970). Moreover, secondary succession on severely burned spots was delayed by several years.

Animal damage may be increased.--Residue treatments affect the amount and type of bird and animal damage to Douglas-fir. When residues are broadcast burned, access to seed and seedlings is improved; greater depredation by birds and large animals is likely. Conceivably, burning could promote growth of shrub and herbaceous plant species which provide more or less attractive animal habitats and alternate food sources to Douglas-fir. Although shade from some plants or unburned slash can aid survival of seedlings, shade may increase seedling damage by animals. Thus, Hermann and Chilcote (1965) reported that losses by animals in newly germinated Douglas-fir increased from 13 percent on open seed beds to 31 percent on lightly shaded, and to 57 percent on heavily shaded (25 percent of full sunlight) seed beds. Most of this mortality was caused by white-footed deer mice clipping cotyledons and stems of newly emerged seedlings. The complex relations of residue treatments and animal damage are reviewed by Dimock (1974).

*Species composition and **stocking** percentages.*--It is generally recognized that lack of burning favors dominance of the associates of Douglas-fir, such as western hemlock, western redcedar, and Pacific silver fir *(Abies amabilis)*. These species are often present as advance regeneration (Hofmann 1924; Morris 1958, 1970) and survive well on nonmineral soil seed beds (Minore 1972). For example, Morris compared stocking of commercial conifers on 4-milacre quadrats within paired plots (burned or unburned) on 30 units in the western Cascades of Washington and Oregon and 8 units in the coastal strip of Oregon. He found advanced reproduction on about half the plot pairs; little of this was Douglas-fir and little survived the slash fires. If seedlings that were established before logging (advanced regeneration) were considered, then his average percentage of stocked quadrats increased approximately 10 percent on unburned and 1 percent on burned plots.

If clearcuts are left unburned, then recent seed and seedlings also contribute to future stocking. Morris' (1958) data indicate the significance of this to subsequent stocking. When he considered seedlings established from seed crops shortly before or soon after logging, he found significantly better average stocking 3 years after logging on the unburned than on the burned plots in both the western Cascade areas (23- vs. 14-percent stocking) and coastal strip (57- vs. 49-percent stocking). However, differences between burned and unburned plots were no longer significant when seedlings were retabulated to compare stocking 3 years after logging and the same number of years after burning.

Morris' continued observations of burned and unburned plot pairs at fewer, selected locations for more than 15 years showed (1) no long-term difference in the percentage of stocking between burned and unburned plots in either location; (2) gradual increase in stocking; and (3) continued higher and prompter stocking in the coastal area than the Cascades, probably due to a greater proportion of prolific western hemlock in nearby stands and to a more favorable climate. The long-term effects of slash burning on species composition and Douglas-fir growth have not been determined in this or other studies; investigations are needed.

Particularly on steep slopes, both moderate and severe burning probably increase seedling losses caused by the downslope movement of soil, gravel, or logging debris which bury or uproot seedlings. Movement of surface material after clearcutting and burning was a major cause of mortality on steep slopes, especially for smaller sizes of planted seedlings (Berntsen 1958). In another field trial in which 5,600 seedlings were planted in five clearcuts on steep slopes in the North Umpqua drainage of southwestern Oregon, first-year mortality ranged from 40 to 80 percent; soil and debris movement was the major cause of this mortality.[5]

Isaac (1949) suggested several options for promoting natural regeneration and still providing adequate protection against accidental fires; most organizations have used these guidelines. (1) spot burn high hazard areas, instead of broadcast burning entire units; (2) avoid burning southerly aspects where slash provides needed shade; (3) restrict broadcast burning to those areas where reasonable protection from fire requires hazard reduction, or where heavy brush development or debris will hinder regeneration; and (4) minimize the fire intensity by burning after early fall rains, as soon as the fine slash dries enough to ignite but while the duff layer is still moist.

In our opinion, these general guidelines remain valid. Their use requires an area-by-area appraisal and decision about the need and most feasible means for reducing fire hazard and securing regeneration. An objective of natural

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[5] Richard E. Miller. Critique of and results from the Glide Ranger District - Reforestation Administrative Study. Unpublished report on file at the Forestry Sciences Laboratory, Olympia, Washington, 22 p., 1965.

regeneration of Douglas-fir requires removal or disturbance of the forest floor at numerous microsites throughout the harvested area. If regeneration is through planting, then the need to provide mineral soil seed beds is replaced by a need to remove physical obstacles and reduce brush competition. Broadcast burning is one of several means for accomplishing adequate site preparation. With high-lead yarding of clearcuts and intensive utilization, the manager's postlogging survey could often show that no additional site preparation is necessary.

Broadcast Burning and Growth

Growth of existing or future stands can be affected by residue treatment.

Effect on existing stands.--Broadcast burning has been the usual method for reducing the extreme fire hazard that frequently remains after clearcut harvests in old-growth Douglas-fir. This practice can affect any advance regeneration within the harvested unit and trees outside the unit. Any advance regeneration remaining after logging is usually of species other than Douglas-fir. Broadcast burning will usually destroy advance regeneration, in species infected by dwarf mistletoe, *Arceuthobium* spp., or balsam woolly aphid, *Adelges* piceae, this may be of little consequence (Nelson and Harvey 1974).

In a properly executed burn, stands adjacent to the broadcast-burned clear-cut will benefit from the lowered risk of wildfire. Minimum edge scorching and slopovers can be expected where residue management was a design consideration. More serious damage has resulted from holdover fire which reappeared days or weeks after slash burning; in most cases, fire-killed trees can be salvaged. We know of no published data about acres of live timber burned from escaped slash fires and the resultant impacts on stand management; however, such data are important for evaluating the true costs and benefits of broadcast burning to reduce fire hazard or prepare a site for regeneration.

Not all Douglas-fir is harvested by clearcutting. Thinning is common; shelterwood harvesting is increasing. Though not currently practiced in the Pacific Northwest, light underburning in the future may be used in residual stands to expose mineral soil or reduce vegetative competition for seedlings. The use of underburning in stands with heavy accumulations of forest floor to reduce fire hazard and stimulate nutrient cycling to the mineral soil has also been proposed (Moore and Norris 1974). Obviously, the potential for damage to residual trees can be minimized by low fire intensity. Piling slash, removing concentrations near trees, and burning under carefully prescribed fuel and weather conditions that permit a controlled fire of the desired intensity are options for the land manager. Since precautionary measures to reduce heat or fire damage to residual trees increase the costs of residue treatment, information is needed to quantify the vulnerability of various tree species to damage and to identify the degree to which precautionary measures must be taken to avoid damage.

Effects on future forest productivity.--Soil productivity is probably reduced to the extent that broadcast burning exposes mineral soil and consumes fine-textured organic matter. Unfortunately, direct evidence that tree growth is actually reduced, even in severely burned spots, is short term, limited, and conflicting. Thus, Tarrant and Wright (1955) found no difference in height and root length of 1- and 2-year-old Douglas-fir growing on severely burned and unburned soil; the soil at the two locations studied was neither stony nor shallow. Yet, Isaac and Hopkins (1937) and Baker and Phelps (1969) observed that severe burning did reduce Douglas-fir seedling growth for at least 10 years after planting. The soil at their respective study sites was also neither stony nor shallow. Unfortunately, the effects of various intensities of burning on Douglas-fir growth have not yet been measured on shallow, stony soils located on steep slopes where soil disturbance and loss of organic matter are most likely to result in soil productivity and Douglas-fir growth.

Slash burning increases the proportion of exposed mineral soil to an additional 8 to 43 percent over that exposed by. harvesting activities (table 2), although this provides more favorable seed beds or makes planting easier; exposed soil on sloping terrain is likely to accelerate erosion and reduce soil productivity.

The effects of slash burning on erosion have been summarized by Dyrness (1966, p. 605):

> . . . although severe burning may alter surface soil characteristics sufficiently to bring about some increase in erodibility, moderate and light burning often have very little direct effect on soil properties. Therefore, the most important changes caused by fire are often not in the mineral soil itself, but rather in the vegetation and litter which protect the soil surface. If essentially all surface fuel is consumed by an intense fire, exposure of mineral soil will often result in decreased infiltration rates largely due to destruction of surface structure by raindrop impact. A light surface fire, on the other hand, will generally only char the litter, leaving most of the mineral soil at least partially covered. In many instances, this remaining litter may afford sufficient protection to maintain soil porosity, and, therefore, to avoid a large-scale increase in accelerated erosion.

To meet his objective of maintaining or improving site productivity, the land manager should be selective in his use of broadcast burning. In our opinion, broadcast burning should be avoided on immature soils which are characteristically stony, coarse-textured, or shallow and in situations where accelerated erosion is likely. When broadcast burning is the most effective way to secure regeneration or reduce the danger of wildfire, an even greater threat to short- or long-term productivity--remedial efforts such as drainage control, fertilizer, and seeding annual cover crops are recommended (Rothacher and Lopushinsky 1974).

EFFECTS OF OTHER RESIDUE TREATMENTS

The need to minimize risk of accidental fires in logging slash, yet avoid air pollution from broadcast slash fires, has stimulated search for, and use of, alternative methods of residue disposal. However, the effects of alternative methods on regeneration and especially on soil productivity and growth of Douglas-fir have not been investigated. Thus, we have only indirect evidence about the effects of these alternatives to slash burning.

When compared with broadcast burning, most other residue treatments (piling, piling and burning, crushing, or chipping in place) have limited application because tractors rather than cable systems are used; thus, operations are generally limited to slopes under about 40 percent. In addition, operations involving heavy machinery on medium-to-heavy-textured soils should be limited to dry periods to avoid soil compaction (Steinbrenner 1971). Additional tractor operations after yarding increase the amount of disturbance to the mineral soil. For example, tractor logging with slash piling on 11 small clearcuts on gentle slopes left an average of only 5-percent undisturbed soil compared with 44 percent after high-lead yarding on a 35-percent slope./ Although additional disturbance exposes more mineral soil seed bed and promotes natural regeneration of Douglas-fir, this disturbance can adversely affect advance regeneration and soil productivity.

Piling Slash

Use of tractors to pile residues can provide sufficient exposure of mineral soil for natural regeneration, further reduction of brush competition for 'light and moisture, and good access for planting and other cultural practices. However, removal of residues and reduction of brush density reduce shade or frost protection for seedlings; on severe sites, this could be catastrophic unless cover is maintained by other means, such as shelterwood.

Piling slash implies additional soil disturbance and loss of organic matter in affected portions of the unit. In clearcut harvests, large material is likely to be piled, yet much fine logging slash and surface soil will also be included unless brush blades are used carefully to avoid soil disturbance. Ordinarily, slash piling by tractors strongly conflicts with prudent soil management since exposure of bare soil or compaction can lead to serious erosion and reduction in site productivity. With exceptional care, reasonable terrain, and dry soil conditions, however, piling residues after logging should not greatly increase the extent of exposed or compacted soil or loss of organic matter from the site over that with broadcast slash burning.

Piling and Burning Slash

Burning piled slash creates hotter fires with less air pollution than broadcast, burns (Fritschen et al. 1970); burning the piled slash further increases accessibility for future cultural practices. Effects on regeneration will be the same as for piling without burning, but the high soil temperatures achieved under the piles will affect the soil even more adversely than under severely burned spots after broadcast burning. We found no existing data on the amount of severely burned area resulting from pile-and-burn operations compared with broadcast burning.

Mechanical Treatment of Slash

Reducing the size of logging slash by crushing or chipping and by leaving slash close to or mixed with the soil can reduce fire hazard and provide conditions for faster decomposition and incorporation of organic matter into the soil. Although specific information is not available, we assume that mechanical treatment would result in (1) retention of most organic matter, (2) sufficient exposure of mineral soil for natural Douglas-fir regeneration, (3) good access for cultural operations, (4) substantial reduction of brush density, and (5) minimum soil compaction where equipment operates largely on an organic

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6/ Personal communication with Dr. C.T. Dyrness, Pacific Northwest Forest and Range Experiment Station, October 1972.

matter "cushion." Possible limitations to mechnically treating slash include,: (1) elimination of advanced regeneration, (2) high cost, **(3)** steep topography, (4) reduced but prolonged slash hazard, and (5) soil compaction where an organic cushion is not present. Where nutrients limit rate of decomposition, positioning large quantities of slash close to or within the soil may cause temporary nitrogen deficiencies; however, applying fertilizer may speed decomposition and directly benefit regeneration. Means for accelerating rates of natural decomposition should be researched.

The difficulty of mechanical treatment increases with size and density of harvest residues; where soil compaction is a potential problem, tractor use should be limited to dry soil conditions. For small trees or good utilization, moving large tractors over brush and logging debris may be sufficient; tractors should follow a twisting path so that tracks disturb the forest floor. However, at the other extreme characterized by large old-growth debris and poor utilization, huge equipment might be necessary to reduce size and height of the slash, create enough spots of mineral soil for natural regeneration, and improve access for subsequent cultural operations.

Removina Residues from Site

The cost and effects of removing residues from the site for use and disposal elsewhere will obviously depend on the size and amount of material removed. These variables and the means for removing the slash will determine the extent of hazard reduction, mineral soi1 disturbance, access for cultural operations, loss of organic matter, and potential for erosion. This residue treatment method is a further extension of current trends toward intensive utilization and YUM yarding; further information is needed to determine situations in which this technique has advantages over other options.

SUMMARY DISCUSSION

The land manager's decisions--if, how, and where to treat forest residues--are admittedly complex; his decisions will depend on relative or absolute values given to various management objectives and their interrelationships. Thus, plans for final harvest of mature and especially overmature stands of Douglas-fir should be integrated with silvicultural plans for regenerating and tending the new stand. Moreover, these plans should be fitted to carefully assessed stand and site conditions which exist or may exist after logging. In most situations, proper choice and execution of logging or residue treatment methods will probably eliminate need for additional site preparation or remedial site restoration activities.

Naturally ***regenerating*** *Douglas-fir*.--Currently, we .have insufficient and frequently contradictory evidence to judge which methods of residue treatment are most likely to provide satisfactory natural regeneration of Douglas-fir. The success or failure of residue treatment will depend on its direct effects on existing seedlings and seed and on indirect effects on environmental factors which are critical for successful regeneration at specific locations.

There is general agreement that mineral soil is the most desirable seed bed for survival and growth of Douglas-fir. Exposed or disturbed mineral soil favors seedling survival by reducing vegetative competition for soil moisture and providing more moderate surface temperatures and moisture relations than those existing on undisturbed organic materials. Yet, treatments which expose mineral soil also destroy overhead cover which provides heat and frost protection and reduces risk of accelerated erosion. Thus, a general need for sufficient, well-distributed seed beds of mineral soil must be balanced against a specific need at some sites to provide adequate shade or frost protection.

Exposed mineral soil may be obtained by mechanically removing or breaking the matted forest floor (duff) or mixing it with mineral soil; the forest floor can also be removed by burning. At four locations in southwestern Washington, mineral soil exposed by mechanical means (logging) provided a significantly higher stocking percentage after aerial seeding of Douglas-fir than that exposed by burning.[7] The amount of soil disturbance accompanying logging operations is controllable so that more or less mineral soil can be exposed; however, this control may increase logging costs. For example, to facilitate regeneration efforts by increasing the amount of soil and brush disturbance normally resulting from skyline yarding systems, chains or tubes with protruding hooks have been dragged back and forth by the yarder after logging (Sommer 1973). If seedlings are to be planted, adequate site preparation can usually be achieved by scalping out seedling locations with hand tools, if access within the units has been achieved through good utilization, slash fires, or machine piling of residues.

In general, any logging method or residue treatment which increases the amount of exposed mineral soil at sufficient microsites throughout the treatment area should rank high for achieving natural regeneration. Broadcast burning can provide an additional 8 to 43 percent exposed or disturbed mineral soil; the increase will be greatest after use of cat and skyline yarding systems which minimize soil disturbance over the logging unit. Stocking percentage of Douglas-fir averaged two to three times greater on burned than on undisturbed seed beds after 14 clearcuts were aerially seeded with Douglas-fir in northwestern Washington (see footnote 7). Where species other than Douglas-fir are acceptable, however, there is little need to expose additional mineral soil by broadcast burning. Thus, there was no difference in average stocking (all conifers) on burned and unburned plots in southwestern Washington and western Oregon (Morris 1970) and burned and unburned milacre plots in western Oregon.[8]

Thus, broadcast burning creates more mineral soil seed beds, but there is no consistent improvement of stocking from natural or helicopter-disseminated seed. Depending on the local situation, burning affects other environmental factors which are critical to seedling survival. For example, Isaac's numerous investigations of natural regeneration of Douglas-fir clearly showed the need for shading to increase initial survival and height growth. He observed that "dead" shade of stumps, logs, and overhead slash was preferable to living shade of vegetation; moreover, that "living" shade of clumpy, shrubby vegetation was more desirable than that provided by continuous stands of herbaceous invaders. Morris (1970) found that broadcast burning did not affect the coverage by

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7/ Ronald Stewart. A study of Douglas-fir aerial seeding. Unpublished report No. 4, Washington State Department of Natural Resources, Olympia, 25 p., 1966.

8/ ,Eugene R. Manock. Unpublished preliminary report, Information No. 5: Seed source effectiveness study. Oregon State Board of Forestry. 1965. On file at Forestry Sciences Laboratory, Olympia, Washington.

herbaceous vegetation but did reduce the proportion of most shrubby vegetation, except where buried ***Ceanothus*** seeds were stimulated into germination, producing characteristically heavy cover. Presumably, other residue treatments would also reduce the proportion of shrubby vegetation but without stimulating *Ceanothus* species and other species in which germination is stimulated by heat.

The effect of logging and residue treatment on existing shrubby vegetation can be significant in securing regeneration. Because of its continuous, rather than clumpy, growth habit, salmonberry is particularly undesirable in the Coast Ranges; thus, any treatment--for example, slash burning--which reduces salmonberry would favor Douglas-fir regeneration. We do not know what effect the increased amount of soil disturbance associated with other slash treatments would have on the distribution and growth of salmonberry. Shrubby vegetation having a more clumpy habit may improve the seedling environment by providing shade or frost protection. Except where fire stimulates the germination of certain brush species, all residue treatments are likely to have at least a temporary adverse effect on growth rate of clumpy vegetation such as vine maple or rhododendron. Thus, with extreme residue treatment, both dead and living shade will be reduced to a minimum. Whether this minimum will still provide sufficient moderation of the seedling microclimate will , of course, depend on the severity of site. When minimum quantities of seed are available, as on adverse sites, we should probably attempt to maximize shade, particularly dead shade of logging slash.

In brush hazard areas, scarification from logaing or light to medium burns seldom provides sufficient well-distributed exposure of mineral soil and removal of competing vegetation to insure adequate natural regeneration of Douglas-fir. For example, on high- to medium-quality sites of the Coast Ranges, a reliable practice is to plant after getting as much scarification as practical with cable logging followed by burning with dry soil conditions. The large reserves of soil nitrogen and rapid vegetational succession on these sites will probably minimize the negative effects of these treatments on site productivity.

Other residue treatments will vary by type of seedling microsite. With the possible exception of some mechanical treatments, such as onsite crushing or chipping of slash, residue treatments should increase exposure of mineral soil and reduce protective cover. 'However, the effects of these methods must be surmised until the various types of microsites resulting from specific harvesting and residue treatment combinations are known and correlated with seedling growth and survival.

Maintaining soil productivity.--As detailed previously, residue treatments can affect short- and long-term soil productivity through immediate effect on vegetation, forest floor, and the surface soil. Subsequent effects will be seen on other natural processes, such as secondary succession and soil erosion, which can remedy or extend the initial effects of logging and residue treatment. Whereas the land manager generally strives to maximize the amount of mineral soil exposed by residue treatment and thus reduce risk of wildfire and costs of regenerating Douglas-fir, this conflicts directly with his general objective to minimize disturbance of the soil to protect soil productivity. Obviously, some tradeoffs are necessary either by accepting loss of productivity or by following residue treatment with some remedial measures to maintain or improve productivity.

Effects of removal or disturbance of residue, vegetation, and the forest floor vary. Minimal reductions in productivity are likely to occur on higher quality sites which commonly have (1) a relatively large capital of nitrogen and organic matter in the mineral soil; (2) deep, well-drained soils with high infiltration rates and moisture-holding capacity; such soils have minimal potential for surface erosion and mass movement, or are less affected if these occur; (3) favorable climatic conditions which compensate for reductions in chemical or physical properties of the soil; and (4) rapid secondary succession by a wide variety of plants which reestablish a nutrient and organic cycle and frequently add nitrogen through symbiotic N-fixation. However, the fact that Douglas-fir growth on high-quality sites can be improved by nitrogen fertilizer suggests that site productivity may have been reduced by past natural or man-caused activities.

Forested areas of low or medium site quality have less total nutrient and organic matter capital and a higher proportion of this distributed on the forest floor and in the stand; both these aboveground sources are vulnerable to destruction by fire. Restricted soil depth or large content of gravel or rock outcrops further reduce the nutrient and moisture storage capacity of the soil. Thus, some soils have less tolerance for losses of nutrient or organic matter through fire or surface erosion. The land manager must choose his logging and residue treatment methods carefully for such sites.

Choosing an appropriate residue treatment.--We set up a hypothetical, yet typical, residue situation in the mid-Oregon Cascades and made the following assumptions:

1. Objective: The manager desires to convert the existing old-growth stand to a well-stocked stand of Douglas-fir for future intensive management for wood production; effects of timber management on this unit must be compatible with current watershed and recreational uses in the entire drainage.

2. Regeneration system: Douglas-fir regeneration is desired; insufficient advance regeneration of hemlock and silver-fir is present. Because of southwesterly aspect and probability of many dormant seeds in the forest floor, heavy Ceanothus development, especially after broadcast burning, is anticipated. Planting is feasible, although at least 25-percent first-year mortality is expected. Residue treatments which reduce heavy slash concentrations (more than 1 foot (30.5 cm) deep) will reduce planting costs, yet these same treatments will reduce dead shade and increase access for deer browsing. Cost per surviving tree will thus depend on the need for shade and deer protection during the first years after planting.

Adequate natural regeneration of Douglas-fir is also possible. This 20-acre (8.1-ha), elongated unit--5 chains by 40 chains (100.6 m by 804.6 m)--is surrounded by mature Douglas-fir; a moderate-to-good seed crop is predicted within 2 years of logging. Residue treatments which leave light slash are probably desirable for seed and seedling survival--providing no accidental fire occurs.

3. Disease: Numerous *Poria* weirii foci are in the proposed clearcut. Infected stumps, roots, and butt chunks are reservoirs of inoculum for renewed infection. These residues should be confined to the existing foci, reduced to smaller sizes, and not pushed into the soil (Nelson and Harvey 1974).

4. Fuels: Despite anticipated close standards of utilization, large amounts of residue--150 tons per acre (336 metric tons per ha)--of all sizes will remain

after clearcut harvest of old growth. Fuel type will be H-X/X, i.e., high to extreme rate-of-spread and extreme resistance-to-control. Ignitibility will be high in rotted wood that is general on area. Rate-of-spread expected to decrease to H-M (high to moderate) in 5 years as the finer flashy fuels deteriorate.

5. Risk of fire: Well-traveled public-use road through unit. Area is subject to lightning storms several days each summer.

6. Fire detection and control: Area is readily visible to aircraft patrol. Reporting time by public traveling through the area, at least 30 minutes to nearest phone; initial attack 45 minutes from reporting.

7. Terrain: Moderate; 30-percent slopes near ridgetop with moderate dissection permit tractor logging and localized piling or crushing of logging slash. Reasonable but not exeptional care must be taken to minimize the disturbance of the mineral soil, especially near streams; earthmoving from spur and skid road construction must be minimal.

8. Soil productivity: Low; this shallow, immature soil has very gravelly, clay loam texture; compaction is likely if tractors are used on bare, moist soil; accelerated sheet and gully erosion are likely where mineral soil is exposed; conservation of organic matter and nitrogen is highly desirable.

9. Water'quality: Increase in suspended sediments in the small stream passing through the unit would cause 'siltation of a nearby recreational lake and should be avoided.

10. Recreation: The unit is readily observed from several, well-visited vantage points; deer hunters and general public will visit the area.

11. Wildlife: Heavy deer usage and seed depredation by birds and mice are expected.

We provide our ratings of several residue treatment methods for obtaining given management objectives on this hypothetical situation (table 4). Only the initial costs of applying a given residue treatment are considered. Obviously, the passive disposal system (natural decomposition) has the least initial costs, and other procedures require added costs; increased disposal costs, however, can encourage better utilization or decrease other costs of management. Mechanically chipping or crushing or machine piling are expensive treatments which are limited in application to those areas accessible to heavy machinery and not subject to soil compaction. Removing residues from the site is probably the most expensive residue treatment considered; for example, experience with YUM yarding by the U.S. Forest Service has shown that removing small logs--minimum of 10 feet (3 m) with 8-inch (20.3 cm) diameter inside bark at large end--increased yarding costs as much as $500 per acre, although some additional utilization did occur.[9]

Rating residue treatments for their effects on attaining satisfactory natural Douglas-fir regeneration proved extremely difficult, even with assumptions about the hypothetical clearcut. Successful natural regeneration requires

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[9] Personal correspondence with Ron Johnson, Forester, Olympic National Forest, October 1972.

Table 4.--*Rating of several residue treatment methods for a hypothetical clearcut* 1/

Management objective and subobjective	Treatment					
	No treatment	Broadcast burn	Pile without burn 2/	Pile and burn 2/	Mechanically treat and leave 2/	Remove 3/
Minimize production costs per acre and per unit of products removed						
Residue treatment	1	4/ 2	3	4	5	5
Douglas-fir regeneration						
Natural	5	3	2	1	4	2
Planted/	5	1	3	2	4	2
Stand accessibility	5	3	2	1	2	4
Protection or risk						
Fire	5	2	3	1	4	3
Insects	5	2	4	1	3	2
Disease	2	2	6/ 4	6/ 3	6/ 5	1
Replacements						
N(S) fertilizing	1	4	3	5	2	3
Erosion control	1	3	4	5	2	3
2. Maintain soil productivity						
Conserve fine organic matter	1	4	3	5	1	2
Minimum disturbance	1	2	4	5	3	3
Minimum compaction	1	2	5	5	3	3
3. Maximum compatibility and benefit to						
Water quality	1	4	3	4	2	2
Recreation	5	3	3	1	2	3
Wildlife	5	2	4	5	1	3

1/ Ratings from 1 (most favorable) to 5 (least favorable) for attaining given management objectives.

2/ Treatment not feasible on steep slopes (exceeding about 40 percent).

3/ Equivalent to YUM yarding.

4/ Potential higher cost because slash fires can escape.

5/ Cost per surviving planted tree (planting costs and survival are variables).

6/ Rate as 2, if slash piled on *Poria* foci or slash chipped and left above **soil** (personal correspondence with Earl Nelson, Research Pathologist, Forestry Sciences Laboratory, Corvallis, Oregon, June 1974).

adequate seed fall, germination, and survival which are uniformly distributed over the clearcut. If one or more of these factors are inadequate, then attaining the management objective of a well-stocked unit soon after the removal of the preceding stand is impossible.

Further refinement of this relative cost:benefit analysis will require measuring the effects of various residue treatments and assigning dollar values to costs and possible benefits from residue treatments. For example, how much is soil fertility reduced? What is the cost of avoiding or correcting this **loss?** Currently, we know that preserving soil fertility is a particularly important management objective on immature soils, which are common to steep, rocky slopes. As land utilization becomes more intensive, forestry is traditionally relegated to soils which are marginal for other uses. Yet immature soils can least afford damage, because soil moisture capacity and nutrient capital are low; moreover, soils on steep slopes are highly subject to damage, because of greater soil disturbance associated with logging on steep slopes and greater potential for erosion. Irrespective of soil type and terrain, the land manager is advised to place the protection of his soil resource high among his other management objectives.

Choice of residue treatment method has fewer complexities and less importance when Douglas-fir is regenerated by planting or when more tolerant tree species are acceptable. Large quantities of slash associated with no residue treatment or minimal treatment adversely affect the initial cost of planting and usually provide havens for small mammals which often use seedlings for food (Dimock 1974); yet in other situations, these same residues can increase survival and growth of the seedlings by being obstacles to radiation and browsing deer. Thus, it is difficult to generalize about the net gain from residue treatment on survival and growth of planted Douglas-fir. For the harsh site of our hypothetical clearcut, we predicted that reducing the amount of slash on the ground would provide the lowest cost per surviving seedling.

CONCLUSIONS AND RECOMMENDATIONS

RESIDUE SITUATIONS AND TREATMENT PRACTICES NEEDING REVISION

We cannot suggest any completely new practices but can emphasize opportunities and precautions that should become routine in the slash disposal decision.

1. Coordinated efforts should be accelerated in the Douglas-fir region toward improving economic climate and interdisciplinary technology for more complete conversion of residues to useful products.

2. A detailed examination of conditions at each location should routinely precede the slash disposal decision; for example:

A. Conservation of organic matter and associated nutrients is particularly critical on steep, shallow, or stony soil, in which a large fraction of the site's nutrient and organic matter capital could be lost by burning or removal. Such soils are extensive throughout the Douglas-fir region; slash burning should not be done routinely on these soils. Moreover, mechanical rearrangement' of the material should be minimized to avoid soil disturbance and redistribution or loss of organic matter.

B. In contrast, on highest quality sites where a smaller fraction of the organic matter and nutrient capital is above the mineral soil, burning of slash may be the most economical or least damaging method for slash disposal and control of competing vegetation.

C. Adequacy and distribution of coniferous seedlings amid the residues should be carefully assessed before residue treatment. Wherever past experience indicates probable failure in reproducing Douglas-fir, we should avoid destroying advance reproduction of this or other species.

NEEDED RESEARCH

1. Develop new and economical uses for unmerchantable material.

2. Establish or reestablish permanent plots to quantify and compare the long-term effects of various fire and nonfire residue treatments on vegetational development and site productivity. For example, the reestablishment of some of the 60 paired-observation plots (burned vs. unburned) that were established in 1946 (Morris 1970) is most desirable. Because his plots and those of others investigating the effects of residue treatments were located on moderately deep, relatively stone-free soils, additional plots will be necessary to sample shallow or extremely stony soils, particularly on steep slopes. Such sites are extensively distributed, relatively uninvestigated, and undoubtedly more susceptible to damage through man's activities; they should receive research priority.

3. Since most of our current knowledge pertains to the effects of broadcast burning, determine the effects of alternative methods of residue treatment. For example, what are the amounts and distribution of various microsites resulting from crushing, removing, or chipping residues? How do these affect the regeneration and growth of Douglas-fir and associated species?

4. Determine the importance of specific forest residues in nutrient cycling and site productivity.

5. Develop a residue treatment index expressing the need for and risks of residue disposal treatment; extending previous work by Fahnestock (1960) in Idaho is desirable. The index should include *at Zeast* the following factors and their interaction:

A. Values to be protected and their susceptibility to damage by wildfire and various methods of residue treatment: estimated amounts of nitrogen contained in the forest floor, logging slash, and soil; percentage of unit adequately stocked with advance regeneration; and potential for soil erosion.

B. Quantity and flammability.

C. Risk and ignitibility.

D. Availability of fire protection.

E. Climate and microclimate.

F. Probable rate of natural decomposition and hazard reduction.

6. Develop an index or decision logic table quantifying the need for site preparation for natural or planted regeneration and the probable costs and risks of various options for attaining this in individual situations.

7. Quantify the vulnerability of various tree species to fire and mechanical damage and identify the degree to which precautionary measures must be taken to avoid 'damage to these species when treating logging slash in thinning and shelterwood operations.

8. Find practical means to increase rate of natural decomposition by modifying physical or chemical properties of the residue or soil; we should be able to reduce fire and disease hazards and improve organic matter and nutrient cycling in our managed stands. Adding nitrogen fertilizer and protecting or planting nitrogen-fixing plants or other plants which provide easily decomposable organic matter are means for increasing the decomposition rate of more resistant residues.

IMPLICATIONS FOR RESIDUE-TREATING EQUIPMENT

1. Accelerate development of equipment capable of removing at least the larger pieces of logging residues at lower costs.

2. Increased utilization will probably reduce slash quantities from regeneration cuts 'in young-growth timber so that burning is not necessary for fire control or access for planting. When natural regeneration is desired, some site preparation measures may be necessary to expose mineral soil sufficiently. On gentle ground, tractors can easily handle this operation. For steep ground, however, there is a need for developing efficient equipment for preparation of seed beds.

CURRENT AND PERTINENT RESEARCH PROGRAMS ABOUT RESIDUE MANAGEMENT, NATURAL REGENERATION, AND GROWTH OF DOUGLAS-FIR

I. University of British Columbia, Vancouver

A. Soils Department and Faculty of Forestry

1. Impact of harvesting on soil properties, means and rate of recovery from harvesting disturbances

2. Studies of high elevation soils

B. University Research Forest

1. Natural and artificial regeneration

2. Mechanization of silvicultural practices

3. Site preparation

II. Canadian Forestry Service Vancouver Forest Products Laboratory

A. Logging methods

B. Complete tree utilization

C. Utilization of forest residues

III. University of Washington College of Forest Resources, Seattle

A. Site preparation and regeneration

B. Effects of sewage sludge on decomposition of forest residues and nutrient cycling

C. Effect of timber harvesting on soil and water

D. Effect of various silvicultural systems on forest residues and regeneration

IV. Weyerhaeuser Company Research Center

A. Effects of logging and site preparation on regeneration

B. Natural regeneration

V. Pacific Northwest Forest and Range Experiment Station

A. Forestry Sciences Laboratory, Olympia, Washington

1. Shelterwood systems for stand regeneration

2. Animal damage reduction

B. Forestry Sciences Laboratory, Corvallis, Oregon

1. Regeneration in southwest Oregon

2. Effect of management practices on nutrient and water cycles

C. Seattle Unit, Seattle, Washington

1. Logging systems

2. Harvesting methods for logging residue reduction

VI. Oregon State University, Corvallis

A. Soils Department

1. Nature and properties of forest humus

B. School of Forestry

1. Soil compaction and tree growth

2. Utilization of forest residues

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REGENERATION AND GROWTH OF WEST-SIDE MIXED CONIFERS

Robert H. Ruth

ABSTRACT

West-side mixed conifer forests include coastal hemlock-spruce, upper-slope true fir-mountain hemlock, and mixed conifers of southwest Oregon. Numerous overmature and defective stands result in large volumes of Zogging residue. Mature stands characteristically have an understory of advanced regeneration, some of which survives the Zogging operation and becomes .intermixed with logging residues. Residue treatments largely determine the fate of these seedlings. Broadcast burning of residues kills most inter-mixed tree seedlings and sets back forest succession to an earlier stage, creating an environment favorable to seral tree species. Forest fZoor materials and Zogging residues often contain an appreciable portion of the total nutrient capital on a site and should not be removed if needed for tree nutrition. Residues should be left on steep slopes to help protect the soil from erosion. Such slopes generally are an unsatisfactory seed bed when exposed to the **sun** *but are satisfactory for tolerant species under the protection of a forest canopy. The residue treatment for a given area should be determined only after careful evaluation of the various effects of all treatment alternatives, not only from the standpoint of regeneration and growth but other forest uses as well.*

Keywords: Mixed conifer forest (Pacific Northwest west side)--site preparation, natural regeneration, tree growth.

INTRODUCTION

Forest residues, often considered only from the standpoint of fire hazard or unutilized wood, are an integral part of the natural forest where they exert important environmental influences. Desirable from one standpoint, and **a** problem from another, the same materials are here classified as residue when, from the standpoint of forest management objectives, they are present in excess, in the wrong place, or at the wrong time. This leads to the definition of forest residues as used in this paper: Forest residue is the living or dead, unwanted accumulation of woody material, including litter on the forest floor, that originates from natural processes and is added to and rearranged by man's activities such as cultural and harvesting operations and land clearing (Jemison and Lowden 1974).

Residue treatments play a major role in management of west-side mixed conifers. Volumes of residues often are large, creating a fire hazard, but stored nutrients and other benefits of residues are also important. Overmature stands characteristically have an understory of tolerant species. This understory may be protected to become the nucleus of a new timber stand or destroyed in favor of less tolerant species. Residue treatments or the decision for no treatment is a key factor in accomplishing the desired objective. The purpose here is to summarize existing knowledge of effects of residues and their treatment on regeneration and growth of west-side mixed conifer forests.

THE FORESTS

Mixed conifers cover 8,200,000 acres (3,321,000 ha) of commercial forest land in western Oregon and western Washington and contain 10 percent of the national softwood timber supply. The climate, topography, and species mixture vary widely. For discussion purposes, these forests are divided into three vegetational areas: *Picea sitchensis* Zone encompassing the coastal western hemlock-Sitka spruce forests; upper-slope true fir-hemlock forests, including the *Abies amabilis* and *Tsuga mertensiana* Zones; and mixed conifer forests of southwest Oregon including the Mixed-Conifer, *Abies concolor*, and *Abies magnifica shastensis* Zones (Franklin and Dyrness 1973).

COASTAL HEMLOCK-SPRUCE

Forests of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) occupy a narrow coastal strip, extend up river valleys, and cover the broad coastal plain on the west side of the Olympic Peninsula. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is an increasingly common associate eastward where hemlock-spruce merges into hemlock-fir or pure Douglas-fir. Western redcedar (*Thuja plicata* Donn) is common in areas with high water tables. Pacific silver fir (*Abies amabilis* (Dougl.) Forbes) becomes a minor associate in Washington increasing northward and with elevation. Red alder (*Alnus rubra* Bong.) often invades recently disturbed sites and overtops conifer seedlings. The hemlock-spruce forests extend northward to Alaska, but only the Oregon-Washington portion is considered here.

The mild, moist coastal environment provides a residue management situation distinctly different from other parts of the Pacific Northwest. Excellent forest growing conditions result in a huge forest biomass (Fujimori 1971), but residue volumes may be high or low depending on defect percentage and utilization standard. For example, clearcutting a mixed old-growth stand on the Quinault Indian Reservation in the early 1960's left 18,604 cubic feet per acre (1,302 m^3/ha) of material 4 inches (10.2 cm) and larger in diameter plus an estimated 20 to 40 tons (18.1 to 36.3 metric tons) of fine material (Dell and Ward 1971). In contrast, defect percentages are low in most young-growth hemlock-spruce that originated after wildfire, blowdown, or harvest cutting. Utilization standards on public lands often require cutting logs to a 6-inch (15.2-cm) top diameter and 80 board-foot volume. Logs containing less than 80 board feet often are sold on a per-acre basis at a low price, thus encouraging utilization of this small material. This leaves a much smaller residue volume. Utilization on industrial lands often is excellent. For example, residues exceeding 4 inches (10.2 cm) in diameter, 4 feet long (1.2 m), and 10 percent chippable material, measured on six industrial forest clearcut areas, averaged 1,332 cubic feet per acre (93.2 m^3/ha).[1/] Adding in the finer material and material less than 10 percent chippable still leaves residue volume far below that from defective old growth. Variations in stand age, defect, and utilization standards cause a wide range of residue volumes for which management decisions must be made.

Fire danger in the coastal strip generally remains well below that in other parts of the Pacific Northwest. Summer precipitation, prolonged cloudiness, and summer fog minimize drought conditions that are so common farther inland, keeping coastal areas moist and usually safe from wildfire. Precipitation varies within the hemlock-spruce type itself, with a June-September rainfall of 13.6 inches (345 mm) in the north near Forks, Washington, and 6.4 (163 mm) in the south at Newport, Oregon (U.S. Weather Bureau 1965). In spite of generally moist conditions, drying east winds do create the possibility of wildfires. Major conflagrations of the past testify to their occurrence in coastal forests.

Except for the Olympic coastal plain, most topography is irregular, abrupt, and dissected by small canyons. Because of this, in some areas forest residues tend to slide downslope and plug stream channels; harvesting operations accelerate this tendency. Generally the soils are deep, relatively rich, strongly acid, and high in organic matter and total nitrogen. The moist, mild climate speeds up the nutrient cycle, and forest residues tend to decay rapidly.

Forest succession generally is toward western hemlock as the climax species. Hemlock is more tolerant of shade than Sitka spruce and commonly predominates in the understory of mixed stands. Heavy thinnings or shelterwood cuttings usually provide enough additional light for some Sitka spruce to come in with the hemlock. But clearcutting is the most common harvesting system and here western hemlock loses its advantage, except for advance regeneration that survives the logging operation. A full stocking or overstocking of both species normally results.

Clearcutting favors Douglas-fir and red alder. Many forest managers prefer Douglas-fir to Sitka spruce because of fir's higher stumpage value and spruce's susceptibility to the spruce weevil (*Pissodes sitchensis*), which retards height growth and causes deformities. They often plant or seed Douglas-fir and remove many spruce trees during thinning operations.

In spite of its nitrogen-fixing ability (Tarrant et al. 1969), red alder is not a favored species. Alder stumpage values are low and, at normal rotations, yields per acre are far below those of mixed conifers. Large areas of red alder are killed with aerial sprays each year to release conifers.

After logging or other disturbance, rapid growth of herbs and shrubs soon forms a closed canopy over forest residues keeping them moist even on warm summer days--too moist for broadcast burning except during unusually dry periods--and promoting decay. This same cover closes over conifer seedlings slowing their growth rate. Some shrubs, particularly salmonberry (*Rubus spectabilis* Pursh) and thimbleberry (*R. parviflorus* Nutt.), sprout vigorously, form dense thickets, and may effectively exclude conifer regeneration.

Dwarf mistletoe (*Arceuthobiwn campylopodum* f. *Tsugae*) infects the western hemlock component of many old-growth and some young-growth stands. Infected

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1/ Melvin E. Metcalf. Personal communication, March 17, 1971.

trees have excessive defect, adding to residue volumes. Infected understory seedlings also may be classified as forest residue; they should be destroyed to control infection in the new stand.

UPPER-SLOPE TRUE FIR-HEMLOCK

The upper-slope mixed conifers occur in the Cascade Range and' Olympic Mountains extending from the Douglas-fir forest at midelevations upward to timberline. Major timber species are:

Pacific silver fir	*Abies amabilis* (Dougl.) Forbes
noble fir	*Abies procera* Rehd.
grand fir	*Abies grandis* (Dougl.) Lindl.
white fir	*Abies concolor* (Gord. & Glend.) Lindl.
subalpine fir	*Abies lasiocarpa* (Hook.) Nutt.
Shasta red fir	*Abies magnifica* Murr. var. *shastensis* Lemm.
western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
mountain hemlock	*Tsuga mertensiana* (Bong.) Carr.
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
western white pine	*Pinus monticola* Dougl.
lodgepole pine	*Pinus contorta* Dougl.
Engelmann spruce	*Picea engelmannii* (Parry) Engelm.
western redcedar	*Thuja plicata* Donn
Alaska-cedar	*Chamaecyparis nootkatensis* (D. Don) Spach
western larch	*Larix occidentalis* Nutt.

Pacific silver fir is the climax species in most localities, but existing. stands vary widely in composition. Most are in various stages of secondary succession following wildfire and contain mixtures of seral species (e.g., noble fir, Douglas-fir, the pines) and climax or subclimax species (e.g., silver fir, the hemlocks, western redcedar). Most stands are past rotation age with the older ones favored for early harvest cutting.

Defect varies widely with stand age and locality and between species. Noble fir and Alaska-cedar have little defect, and harvest cuttings leave relatively little residue. Western hemlock and Pacific silver fir often are very defective, and large volumes of residue are left in the field. Other species are intermediate in defect. Young stands generally are healthy and relatively free of defect. In general, residue volumes are high because of the high proportion of old-growth timber. As in hemlock-spruce forests, after old growth is harvested and replaced by vigorous young stands, residue volume will decrease.

Forest residues decay slowly in the cooler parts of upper-slope forests. Annual precipitation varies widely but averages about 90 inches (2286 mm). Much of it accumulates in winter snowpacks. Residues tend to be borne to the ground by the snow, but cold temperatures and high moisture content of the wood slow action of decay organisms. Fire danger increases during the summer and may become extreme; in addition, this upper-slope area is subject to summer lightning storms.

Podsolization is the major soil forming process, and soils range from Podzols and Gley Podzols in the north to Brown Podzolic in the south. Average depth of the forest floor is 1.8 inches (4.6 cm), but the range is from about

5 inches (12.7 cm) in the north to almost no accumulation in the south. Average weight is about 28 tons per acre (62.7 metric tons/ha). A duff mull forest floor type is common in the Mount Baker area with litter, fermentation, and humus layers overlying the A1 soil horizon. In the Mount Rainier, Mount Adams, and Mount Hood areas, the forest floor may be of the felty mor type with the A1 horizon usually absent, or of the fine mull type with the humus layer absent. The felty mor type predominates in the Willamette, Three Sisters, and Crater Lake areas in the south. Based on 46 sample stands throughout the Cascade Range, 12 to 26 percent of the supply of major nutrient elements is tied up in this forest floor material (Williams and Dyrness 1967). The forest floor often forms a densely matted layer which, when exposed to the sun, becomes very dry--an inhospitable seed bed for germinating seedlings--and steadfastly resists penetration by a planting hoe (Ruth 1963).

Preferred species for planting or seeding usually are Douglas-fir at the lower elevations bordering the Douglas-fir forests, and noble fir elsewhere within the range of this species. Western hemlock, Pacific silver fir, and other upper-slope species seed in naturally to make mixed conifer stands.

MIXED CONIFERS OF SOUTHWEST OREGON

In southwest Oregon the floras of the Pacific Northwest intermingle with those of northern California and form an array of vegetation types ranging from low chaparral in the dry interior valleys to cool, moist conifer forest at high elevations and near the coast. Most harvest cuttings and residue problems are in the Mixed-Conifer, ***Abies concolor***, and *Abies magnifica shastensis* Zones (Franklin and Dyrness 1973). Only these three zones will be discussed here.

The Mixed-Conifer Zone ranges from about 2,450 to 4,600 feet (750 to 1,400 m) in elevation in the Cascade Range. It merges into the ***Abies concolor*** Zone which occurs in a narrow band up to about 5,250 feet (1,600 m). The *Abies magnifica shastensis* Zone occurs from about 5,250 to 6,560 feet (1,600 to 2,050 m). Similar zones occur at slightly higher elevations in the Siskiyou Mountains.

Southwest Oregon has a complex geology and highly variable soils. Of particular importance here are the soils derived from schists and gneisses, pumice soils at higher elevations, and Pleistocene sands along the coast. They may erode rapidly if exposed to surface runoff and need to be protected by a vegetative cover or by a mantle of forest residues. Other soils may be quite infertile and need nutrients stored in onsite organic material.

The climate of southwestern Oregon is characterized by hot, dry summers, low humidity, high fire danger, and occasional lightning storms. The area has a long history of fire; most forest stands originated after fire. These stands are now in various stages of secondary succession and contain both seral and climax species. Wildfire and often clearcutting have led to development of brushfields or poorly stocked timber stands intermixed with brush (Gratkowski 1961, Hayes 1959). During rehabilitation, the brush itself becomes a major residue problem. At present, in southwest Oregon, shelterwood systems often are preferred over clearcuttings which expose both forest residues and new seedlings to desiccation in the hot sun. With shelterwood cutting, residue management must be accomplished initially in the presence of an overstory stand and subsequently in the presence of established tree seedlings. Residue volumes are high after the initial cut in old-growth timber.

RESIDUES FROM THINNING

Most thinnings in west-side mixed conifers have been in the coastal hemlock-spruce timber type where good seed production coupled with shade-tolerant species results in particularly dense stands. In upper-slope forests, few thinnings have been made because of a limited road network, limited market for small material, and the preponderance of overmature stands in need of harvest cutting. In southwest Oregon, most partial cuttings have had a regeneration objective and, therefore, properly are termed shelterwood cuttings. Residue volumes usually are more than from thinning but less than from clearcutting.

Precommercial thinning often is the first cultural operation in a forest rotation that leaves residues. In coastal hemlock-spruce, precommercial thinnings usually are made when the stand is 10 to 22 years old and diameter of trees to be thinned ranges up to about 5 inches (12.7 cm). Trees selected for thinning are treated with herbicides or are cut with powersaws near the ground. The powersaw method is gaining favor (Hansen 1971). Chemically treated trees deteriorate slowly, losing needles first, then twigs and limbs. Finally, the roots deteriorate and the stem topples. When trees are cut with a powersaw, many remain standing, held up by branches intertwined with uncut trees. Most fall to the ground, but even then, main stems usually are held above ground by protruding branches.

Precommercial thinning residues become a fire hazard whenever they dry. The small, lightweight material favors a high rate of spread. The intertwined stems above ground level severely obstruct movement and increase resistance to control. However, after 5 to 7 years, most stems have dropped to ground level and decay is well advanced. Precommercial thinning residues generally are left untreated with extra fire protection provided during the few years of increased fire danger.

Residues from precommercial thinning degrade the appearance of a young stand. A proposed solution is to leave a roadside strip unthinned to screen the main area from view. After thinning residues have dropped down and merged with the ground vegetation, the narrow roadside strip would be thinned and the residues from it run through a chipper.

Residues from commercial thinning in coastal forests are left untreated, lopped and scattered, or piled and burned. Generally the volume is small and does not constitute a significant fire hazard in the moist coastal climate. The. material involved is small enough to decompose rapidly. Usually it is not a serious obstruction to future management activity. In fact, occasional' huge stumps and logs from the preceding old-growth forest may be more of an obstruction. Little machine piling has been done, most of the work being accomplished by hand. Often only logging residues along roads are treated because the risk of man-caused fire is greatest here. Away from the roads, residues usually are left to decay where they fall. Establishment of regeneration is not a specific objective of thinning, so no residue treatment is indicated for this purpose. If large-scale residue treatments become necessary, they will be difficult to accomplish with mechanical equipment because coastal forests have so many stems per acre and maneuvering among the trees would cause damage.

EFFECT OF RESIDUES ON REGENERATION AND GROWTH

Forest residues are both beneficial and harmful to regeneration and growth of west-side mixed conifer forests, with harmful effects often predominating after logging. Individual effects, good and bad, need careful consideration. Their balance before treatment, expected balance after treatment, and harmful effects of the treatment itself form the basis for residue management decisi'on.

FAVORABLE EFFECTS

An important favorable effect of forest residues in west-side mixed conifer forests is the protection they provide to the basic soil resource. The soil must be preserved for regeneration and growth of succeeding timber crops as well as for other forest uses, particularly in the northern Washington Cascade Range. Here steep slopes, shallow soils, and heavy rainfall are common.

Forest residues protect the soil from erosion: by forming a mantle to protect the mineral soil from the impact of raindrops, by holding back downhill movement of soil during winter storms or during periods when dry ravel may occur, and by shielding the soil from disturbance by wildlife or man. Similar steep slope-shallow soil conditions occur sporadically throughout mixed conifer forests, so the soil protection factor should always be evaluated before residue management decisions are made. The importance of residues to soil protection is discussed by Rothacher and Lopushinsky (1974).

On mixed conifer sites, forest residues often serve as a storehouse for an important part of the nutrient capital. Depending on the residue volume and fertility of the mineral soil, they contain variable proportions of the total nutrient supply. The proportion is high in podzol soil areas with thick accumulations of mor humus, lower in coastal areas where residues decay rapidly. Residues can be left to decay slowly or treated to speed up nutrient release. In the latter case, some nitrogen will be lost to the atmosphere.

The decay of organic material and its incorporation into the forest soil usually improves water infiltration rate, water-holding capacity, and soil aeration. Residues shade the soil surface and reduce evaporation. Lethal soil surface temperature and drought are limiting factors in some areas--there residues should be left on the site.

Residues often provide the shade needed for seed germination and seedling establishment. Particularly in southwestern Oregon but wherever seedlings would be exposed to the hot summer sun, this shade can be the difference between life and death of tree seedlings. It reduces the level and duration of lethal soil surface temperatures, a common killer of germinating seedlings (Hallin 1968a). It slows evaporation from the soil surface, reducing moisture tension in planted seedlings. On the Dead Indian Plateau in southwest Oregon, for example, 2-year. survival of seedlings that were shaded on their south and west sides by logs, bark, or rocks was 60 percent compared with 10 percent for unshaded seedlings (Minore 1971). A common prescription is to plant seedlings in the shade of logs or stumps to protect them from direct sunlight. Most natural seedlings become established on such protected microsites (Isaac 1938).

Frost damage is common on some mixed conifer areas, and the presence of residues near seedlings intercepts outgoing longwave radiation and tends to slow nighttime cooling. Residues also slow cold air drainage. The net effect varies, but the presence of forest residues does reduce frost damage on numerous microsites. Microclimatic effects are discussed in detail by Fowler (1974).

Residues also limit access to mixed conifer seedlings by cattle and big game, thereby reducing browsing damage. On the other hand, residues provide shelter for the small mammals that damage seedlings. Again the net effect varies. Dimock (1974) discusses this matter in detail.

UNFAVORABLE EFFECTS

Certainly a major unfavorable effect of forest residues on mixed conifer seedlings is the threat of wildfire with consequent destruction of the intermingled seedlings, perhaps nearby timber as well. The danger is high in southwest Oregon and upper-slope forests, lower in the moist coastal strip. Fire hazard aspects of residues have been covered by Martin and Brackebusch (1974).

When exposed to the elements, forest residue seed beds generally are unsatisfactory for natural regeneration. An organic seed bed dries rapidly in the sun and frequently develops surface temperatures lethal to germinating seedlings. Particularly in clearcut areas, forest residues become a barrier to seeds' reaching microsites where they can become established 'and grow. The mor humus layer (duff) of the forest floor is generally an unsuitable seed bed under exposed conditions. This problem may be turned to an advantage by residue treatment and site preparation. Treating an area to leave an optimum number of well-distributed mineral soil seed beds. interspersed with organic matter that would result in a fully stocked but not overstocked timber stand should be possible. The clumpy appearance of many timber stands often is the result of an uneven distribution of suitable seed beds.

In coastal hemlock-spruce forests, seed beds often are kept moist by summer fog and drizzle. Here, forest residues have more potential as suitable seed beds than in other areas, but success depends on the stage of decay of the organic material. Fresh logging residues are unsuitable seed beds, but decayed material may be quite satisfactory. For example, Berntsen (1955) examined a clearcut area 6 years after logging and found seed beds of rotten wood 97 percent stocked compared with 83 percent for mineral soil. The difference was attributed to competing vegetation which did well on mineral soil and tended to crowd out tree seedlings. The competition did not do well on rotten wood, and tree seedlings essentially were free to grow. Areas classified as heavy slash were 67 percent stocked.

Morris (1958, 1970) reported on paired plots; one of each pair was broadcast burned and the other left unburned. Nine of the pairs were in coastal forests where natural regeneration became established on both mineral soil and organic surfaces with no preference noted. On the other hand, Minore (1972) reported that neither rotten wood nor duff-covered mineral soil were good seed beds when exposed to full sunlight. Successful seedling establishment probably depends on moisture conditions during germination and initial radicle penetration into the seed bed. A few warm, dry days during the spring will dry the seed bed surface and permit surface heating (Ruth 1967). Organic surfaces get hotter than mineral soil surfaces and cause more seedling mortality.

Under the protection of a forest canopy, residues are less of a seed bed problem. Fresh logging residues still are unsatisfactory seed beds,. but as decay takes place and duff accumulates on logs and stumps, residues become acceptable seed beds. The tolerant species such as western and mountain hemlock and Pacific silver fir commonly become established on residue materials in the moist environment of the understory. Under coastal stands where there is less than 40 percent full sunlight, seedlings usually are larger and more abundant on rotten logs than on the duff-covered forest floor. When sunlight is over 40 percent, seedlings do equally well on these two seed beds. Sitka spruce also will become established on decaying residue material if the overstory is moderate or less in density.

Rotten wood has been shown to be a suitable planting medium in the coastal hemlock-spruce type(Berntsen 1960) but is avoided in other mixed conifer areas. Residue as an obstacle to .planting is discussed by Edgren and Stein (1974).

Forest residues cause seedl ing damage and growth reductions in several incidental ways. A common problem is for bark to slough off a log or stump and cover nearby seedl ings. Some. seedl ings become established under logs or large limbs, only to have the leader grow up into them and be damaged or grow around them causing a deformity. Sometimes residues settle to the ground and crush seedlings. Other seedlings are damaged as their leaders sway in the wind and rub against residue materials. Residues provide shelter for small mammals that consume seed and damage tree seedlings. On flat areas, residues may plug stream channels, raise the water table, and destroy the forest crop.

A continuing unfavorable effect of forest residues in old-growth mixed conifer forests is the physical obstruction to intensive management. Cull logs, stumps, and piles of debris hinder men and equipment during thinning and other cultural treatments of young stands. Some obstruction may persist until the next harvest cut. Stand treatments may be deferred or rejected because of the residues and the growth potential of the site not fully realized.

EFFECTS OF RESIDUE TREATMENTS

The several effects of residue treatments on regeneration and growth of trees mentioned in other sections of this compendium (Miller et al. 1974, Seidel 1974, Gratkowski 1974) are generally effective in the mixed conifer forests west of the Cascade Range. Burning is the most common residue treatment, and the effects of burning on natural regeneration and nutrition are particularly important.

GENERAL EFFECTS OF BURNING

Residue treatments by burning have profound effects on timing of seedling establishment and species composition of mixed conifer stands. Seedlings frequently are present under mature stands and, even with clearcutting, may survive the logging operation to form at least the nucleus of a new stand. Portions of an area may be fully stocked with trees, others not, presenting a clumpy appearance. Some areas, particularly in the hemlock-spruce type, may be fully stocked throughout, with some overstocking. The residues are intermixed with the seedlings. A conservative residue treatment such as hand piling, perhaps with burning, could be designed to protect these seedlings, thereby getting several years' headstart on the new rotation. A general treatment such as broadcast burning could be designed to destroy them, thereby delaying stand establishment. With no treatment, the new stand normally will be dominated by the tolerant species from the understory. The no-burning approach also leaves more fire hazard and increased risk of loss from wildfire.

On the other hand, broadcast burning reduces the fire hazard. Besides eliminating most of the advanced regeneration, such burning opens up the area for seeding and planting. It also creates a more open, exposed environment, generally favoring the less tolerant, seral tree species. Broadcast burning, therefore, rolls back forest succession to an earlier stage. If seral rather than climax tree species are preferred, as often is the case, this is a favorable result.

But succession may be set back too far. Particularly in some upper-slope and southwest Oregon areas the site may become so severe that seedling establishment is delayed or prevented with ensuing loss of productivity. Often this problem may be avoided by prescribing a lighter intensity fire that will leave enough residues to provide shaded microsites for seedling establishment. Under extreme conditions it may be necessary to grow a crop of brush or unmerchantable tree species to again develop an environment suitable for merchantable tree seedlings to become established.

Where tolerant species are acceptable, the best approach usually is to utilize advanced regeneration. The decision to do this, however, means that logging residues will be intermixed with tree seedlings with all the difficulties of residue treatment that this involves. Increasing use of the shelterwood system in west-side mixed conifers emphasizes the importance of this residue problem. With shelterwood cutting, the problem varies with rate of removal of the mature stand. Clearcutting with protection of advanced regeneration, which may be regarded as a one-cut shelterwood system, leaves all the logging residue at one time. On the other hand, a classical shelterwood cutting with a preparatory cut, seed cut, and several removal cuts leaves logging residues periodically for several years with time for some decay to take place between cuts. A residue treatment decision must be made after each cut.

Burning of residues changes the postlogging environment, particularly seed beds where seeds must germinate and seedlings grow. When the result is exposed mineral soil, the chances for natural regeneration are improved. Mineral soil does not heat up as rapidly and provides a more reliable moisture supply than organic material. When the result is blackened organic surfaces exposed to the sun, the high surface temperatures often kill freshly germinated seedlings (Isaac 1938, Silen 1960). With some exceptions, most mixed conifer seed beds are irregular enough to provide small shaded microsites where seedlings can become established. The average depth of residues is reduced by burning, making it easier for seedling roots to penetrate to mineral soil.

Besides its effect on tree seedlings and seed beds, burning kills or damages other live vegetation that may be present. This facilitates subsequent establishment of desired tree seedlings by reducing vegetative competition for light, water, and nutrients. In some situations such as moist coastal environments, burning may be prescribed almost solely for control of vegetation, the reduction in logging residues being only an incidental result. In other situations, such as *Ceanothus* areas in southwest Oregon, burning stimulates germination of seed stored in the soil and may aggravate the competition problem (Gratkowski 1961, Morris 1970). Logging and residue burning have several important effects on nutrient availability. Felling trees disturbs the mineral cycling processes within the forest ecosystem by abruptly stopping mineral uptake. Some of the nutrient capital in these trees is hauled out of the forest, and the remainder, which includes the small but nutrient-rich leaves and twigs (Cole et al. 1967), is scattered about as forest residue. Burning the residues further depletes this nutrient capital by volatilizing much of the nitrogen. Losses of other nutrient elements are less, most of each element being deposited in the ash (Knight 1966, Allen 1964, Grier 1972). Some of this ash is carried away on convection currents during the fire (Grier 1972). Burning has important chemical, physical, and microbiological effects on the soil itself, partly from the heat of the fire but mostly from materials being leached from the ash layer into the soil (Ahlgren and Ahlgren 1960). These effects are discussed in detail by Moore and Norris (1974).

An important effect of burning on nutrition is on timing of nutrient availability for tree growth. Burning rapidly extracts nutrients from residues and deposits them in the ashes. Subsequent rains leach these nutrients into the soil where, for the most part, they become available for uptake by plants. Thus, nutrients accumulated over a period of many years are made quickly available. This quick availability is at the expense of slow release of nutrients through the decay process. Which schedule is more favorable to tree nutrition is not well known. The burst of nutrients from the ash often contributes to a lush growth of herbs and brush which compete with tree seedlings for critically short summer moisture, a particularly important factor in southwest Oregon (Hallin 1968b). A similar problem occurs in moist coastal forests, but here light appears to be the most limiting factor (Ruth 1956). Nutritional demand by trees increases as they develop and become dominant in the ecosystem.

Calcium and other salts included in the leachate make the soil more alkaline, a condition often more favorable to competing vegetation than to conifers. This alkalinity is short lived, however. Coastal mixed conifer soils with an average pH of 7.1 immediately after burning averaged a near-normal pH of 4.6 after 4 years. This compares with nearby unburned soils where the pH ranged from 4.3 to 4.5 during the same period (Tarrant 1956).

BROADCAST BURNING

Whenever mixed conifers are harvested by clearcutting, broadcast burning becomes an alternative treatment. This affects tree nutrition and advanced and postlogging regeneration, both natural and artificial. Artificial regeneration is discussed further by Edgren and Stein (1974).

<u>In coastal forests,</u> broadcast burning destroys most western hemlock advance regeneration and creates conditions that temporarily favor Douglas-fir and red alder over the hemlock. Sitka spruce is intermediate. Since Douglas-fir often is preferred as a replacement for Sitka spruce because of Douglas-fir's higher value and the spruce weevil problem, many consider this a favorable result. Generally, the fir is planted promptly without waiting for natural seeding. The planted seedlings have a better chance of keeping ahead of the competing vegetation than would natural regeneration. A decision to plant Douglas-fir is itself an argument for burning because burning sets back competing vegetation already present and opens up the area for the planting crew (Morris 1970). Some hemlock usually survives the fire. Hemlock and spruce usually seed in later to make a mixed stand.

When the site is being managed for conifer production, the additional red alder that seeds in following burning is an unfavorable result because alder overtops and suppresses conifer seedlings. When this occurs, the alder often is controlled by acceptable aerial sprays.. Standing dead alder stems are an addition to the residue volume. They deteriorate rapidly, however, and residue treatments seldom are necessary.

Broadcast burning usually is accomplished earlier in the fall in coastal forests than in other parts of the Pacific Northwest because of the moist climate. Fire danger may be extreme farther inland when the fuel moisture content in the coastal fog belt is barely low enough for a fire to run broadcast across a clearcut. Seldom does it get dry enough for a severe burn in which the soil is baked red and physical soil properties adversely affected. Morris (1.970) classified the intensity of broadcast burning on nine clearcuts and found only 0.1 percent of the area severely burned.

Preburn spray is a treatment applied mostly in coastal forests when herbs and brush invade a clearcut prior to residue treatment. They shade the residues and prevent them from drying out enough to carry fire; yet burning may be needed to open the area for natural regeneration and planting. The spray kills most of the aerial portions of the plants, the leaves dry and curl, and the sun gets through to the logging residues. The spray-killed vegetation helps carry fire across the area. Without a preburn spray, such an area could be burned only under very hazardous conditions or might not burn at all. Such invasion by herbs and brush is common on some coastal sites. The spray-plus-burning treatment usually kills competing vegetation to ground level and, hopefully, planted tree seedlings will keep ahead of the regrowth that usually occurs. Large planting stock is used when available and postplanting sprays may be needed to hold back the competing vegetation until it is overtopped by the conifer seedlings. Preburn sprays usually are applied from the air.

Generally, the trend is away from broadcast burning in coastal forests because of the moist climate, presence of advance regeneration, improved utilization standards, more harvest cuttings in young stands that have little defect, and smoke management restrictions. An increasingly common practice is to not burn at all or to restrict burning to the landing area and perhaps a few heavy slash concentrations. There are, however, heavily decayed old-growth stands or open stands with heavy brush understories where burning still appears to be a necessary treatment.

In upper-slope forests in the Cascade Range, areas of high residue volume and high fire hazard are strong arguments for broadcast burning after clearcutting. Here, most advance regeneration is Pacific silver fir. At midelevations, and these are the most productive sites, this species is severely damaged by the balsam woolly aphid ***AdeZges piceae*** and is a poor risk as a component of a new timber stand. Destruction of silver fir advance regeneration during broadcast burning favors other species. The burning also sets back competing vegetation, exposes additional mineral soil for natural regeneration, and facilitates planting. The fire often does not consume the mor humus layer which mostly remains blackened but intact as an inhospitable seed bed and obstacle to planting (Ruth 1963).

At higher elevations, the climate is more severe and the sites less productive. Aphid damage is less serious, but getting a new stand started is more difficult, and fewer species are available to choose from. Protecting any advance regeneration that may be present *is* considered good insurance.

Burning days are severely limited in almost all upper-slope areas. Spring burning generally is bypassed because snowdrifts limit access and cover parts of areas scheduled for burning. The rapid transition from snowpack to severe fire weather limits the time available for burning and increases the danger of a smoldering fire spreading out of control later. Fall burning also is limited because rains come early at high elevations. Smoke management restrictions further limit burning, though these are less difficult to meet at high elevations. The result is that it may take several years before a clearcut scheduled for burning can actually be burned. This requires an annual reevaluation of the area to determine whether or not the burning prescription should be continued. These problems are contributing to a buildup of unburned residue on some upper-slope management units.

Particularly in the high elevation forests but at midelevations as well, the general trend is away from broadcast burning. The burning season is short, utilization is improving, and smoke management restrictions often would delay the work. In spite of this trend, however, broadcast burning necessarily remains an important management tool in high hazard areas.

Broadcast burning helps eradicate dwarf mistletoe-infected seedlings. Seedlings in the understory of infected stands invariably have the disease, and unless destroyed, carry it to the next rotation. A recommended procedure is complete overstory removal followed by burning of seedlings along with other residue material.

YARDING UNUTILIZED MATERIAL

Yarding unutilized material (YUM) is a contract requirement on many public timber sales. The contract requires that, in addition to removal of merchantable material, all other material meeting specified dimensions regardless of defects must be yarded to the landing. Hopefully, once yarded, it will be taken to a utilization plant. The dimensions usually specified in mixed conifer forests are 8 inches (20.3 cm) or larger on the large end and 10 feet (3.05 m) or more in length. A 12-inch (30.5 cm) diameter also may be used. This procedure removes the large material, leaving only smaller pieces which decay more rapidly. YUM damages more advanced regeneration than taking only merchantable logs. On the other hand, it usually reduces fire hazard to the point that burning is not required, thereby saving the regeneration that survives the yarding. YUM exposes additional mineral soil seed beds and opens the area for planting. It eliminates many of the physical obstructions to thinning and other cultural operations essential to intensive management of the new timber crop for maximum timber production.

PILING AND BURNING

Piling forest residues with a brush blade mounted on a crawler tractor and burning the piles is another common residue treatment in west-side mixed conifer forests. A variation, particularly when dealing with high residue volumes, is to push the material into windrows and burn the windrows. A brush blade that will pick up the residues but sift out the mineral soil is much preferred for the piling job. A straight bulldozer blade picks up too much soil along with the organic material, making the piles and windrows difficult to burn. When soil is mixed in, the fire may smolder for days, thereby adding to the fire hazard.

Piling and windrowing, even without burning, facilitate future cultural operations by concentrating residues on a small portion of the area. With burning, the area is opened still more for intensive management.

Piling and burning usually has two main objectives, hazard reduction and exposure of mineral soil seed beds. This treatment is used on some clearcuts in upper-slope and other mixed conifer areas where, otherwise,.the mor humus layer would prevent seedling establishment. Teeth on the brush blade break up the humus layer with some of this organic material getting mixed with the mineral soil and some going to the slash piles. If the hazard reduction objective is minor relative to exposure of mineral soil seed beds, piles and windrows may be left to deteriorate naturally. Machine piling and burning generally expose more mineral soil seed beds than broadcast burning. This helps regeneration but can be a disadvantage if an erosion problem exists. Generally, machine piling is limited to moderate slopes where erosion hazard is low. Also, cost of operating crawler tractors becomes increasingly important with increasing slope.

Residue treatment techniques are not well developed for thinning or shelterwood cuttings in mixed conifers on steep slopes. Some hand piling and burning is being done, but costs are high, and only fine residues can be handled.

Piling and burning is a standard residue treatment in most southwest Oregon and upper-slope areas harvested by the shelterwood system. Residues are pushed away from the crop trees and into piles which may be burned later under favorable weather conditions. The piles often are covered with waterproof material and not burned until the surrounding area has been wet down by rainfall , a procedure largely eliminating the possibility of wildfire starting from residue burning. However, heat radiating out from burning residue piles may kill the cambium on the near side of surrounding crop trees. This affects their growth and eventually provides entry for disease. The problem is common where residue volumes are high and residual trees closely spaced. However, consequences are minor if the overstory will be removed before decay and growth reductions would cause an economic loss.

Running equipment over the soil and scraping its surface with a brush or bulldozer blade damages near-surface roots of residual crop trees. Extent of damage varies with nearness of the roots to the surface, soil physical properties, moisture conditions, pressure exerted by the equipment, and care taken by the operator. An additional entry for disease may be provided through the root system. This disturbance, in addition to exposure of tree crowns from the shelterwood cut itself, causes some trees to uproot during subsequent storm winds. Soil compaction is another unfavorable effect, although how much it lowers the productivity of mixed conifer sites is unknown. When a shelterwood overstory will be retained only a few years, volume losses are reduced. If it is to be retained many years, losses may be substantial. Effects of soil compaction and buildup of disease organisms in the soil will carry over to the next rotation.

Machine piling and burning after shelterwood cutting in mixed conifers also affects any advanced regeneration that may be present. This will be favorable if the regenerating species are unwanted, unfavorable if they are needed for the next rotation, Both situations may occur at different times on the same area. Consider, for example, the mixed stand containing some mistletoe-infected western hemlock. Logically, the first shelterwood cutting would remove the infected overstory trees, thereby eliminating the mistletoe seed source. Advance hemlock regeneration should be destroyed during the subsequent piling and burning operation. After new seedlings have become established on the exposed mineral soil, the overstory will be removed in one to several steps. Residues left after overstory removal will be intermixed with the seedlings, most of which need to be protected during any residue treatment that may be applied. Techniques for doing this are not fully developed.

Understory vegetation often gets uprooted and piled with other forest residues, thereby greatly reducing this vegetation as a competitor for moisture and nutrients. This facilitates establishment of tree seedlings and, to the extent moisture and nutrients are limiting, also benefits crop trees in the shelterwood overstory. Piling forest residues redistributes their nutrient capital to small circles that cover only a small percentage of a treated area. The main part of the area may suffer a nutrient deficiency, but trees growing near residue piles would have better than average nutrition.

When residue piles are burned, they produce very hot fires that may bake the soil underneath. The resulting physical effects of reduced percolation rate and increased temperature extremes are, at least temporarily, detrimental to establishment and growth of conifer seedlings.

If residues are piled after dissemination of tree seed in the fall, much of the seed is lost in the piles. Natural regeneration then must wait 1 or more years for another seed crop.

. OTHER TREATMENTS

Residue treatments in west-side mixed conifer forests generally have been limited to the conventional methods--broadcast burning, burning concentrations, piling or windrowing and burning, YUM, lopping and scattering, and no treatment. Mechanical treatments using heavy equipment to crush and chop the residues certainly should not be ruled out, but high residue volumes, a large number of stumps, and steep slopes have discouraged trials of mechanical treatment. Chipping mixed conifer residues has similar drawbacks, but neither should this method be ruled out. As pointed out by Aho (1974), reducing organic material to small chips speeds decay, but the rapidly increasing population of decay organisms temporarily ties up nitrogen that may be needed for growth of tree seedlings. No records have been noted concerning trials of pit or incinerator burning or burying of residues.

CONCLUSIONS AND RECOMMENDATIONS

Treating logging residues or leaving them untreated has important effects on regeneration of conifer seedlings and probably on subsequent growth of the forest crop. Unfortunately, few specific studies have been made of residue-seedling relationships in mixed conifer forests. The following conclusions and recommendations, therefore, are general. Their focus is on regeneration and growth. Residue management decisions must be made recognizing regeneration and growth as important factors but still only part of the wide array of factors to be considered. Trade offs will be necessary when treatments favoring regeneration and growth conflict with other land management objectives.

1. Harvesting an overmature mixed conifer stand or one killed by insect or disease may leave such huge residue accumulations that they physically obstruct establishment of tree seedlings on the site. A high residue volume is a fire hazard to seedlings that do become established and an obstruction to intensive management of the new stand. Residue treatment is recommended to open seed beds for natural or artificial regeneration, reduce the fire hazard, and facilitate future silvicultural operations. The most appropriate treatments are broadcast burning, YUM, or both.

2. A huge residue accumulation should be a one-time-only problem on most sites. Intensive management during subsequent rotations and harvesting at rotation age rather than many years later when stands become more defective should reduce future residue volumes.

3. Improved utilization of material that otherwise would be left as forest residue will in general benefit regeneration by leaving more mineral soil seed beds, reducing fire hazard, and minimizing physical obstacles to intensive management.

4. On steep slopes and shallow soil, the mantle of forest floor material and logging residues helps protect the soil resource from erosion. Residues should not be removed from such areas by yarding or burning.

5. On nutrient deficient forest soils, the nutrient capital stored in forest residues is needed for tree nutrition. Logging residues should not be removed from these areas unless nutrients are replaced by fertilization.

6. Broadcast burning sets back forest succession and establishes an environment more favorable to seral than to climax tree species. If seral species are desired, residue treatment by broadcast burning is indicated. This will destroy most of any advanced regeneration of tolerant species and open the area for seeding, planting, or natural seed fall of desired species.

7. At high elevations in the Cascade Range where starting a new stand is difficult, advance regeneration of Pacific silver fir and other species should be protected and utilized for the new timber stand. Broadcast burning should be held to the minimum required by fire hazard and other factors.

8. When desirable seedlings are intermixed with logging residues, broadcast burning should be avoided. If residues must be treated, care should be taken to leave a full stocking of well-distributed seedlings. If stocking is incomplete, then site preparation should be incorporated into the residue treatment.with the objective of preparing appropriate seed beds for natural or artificial regeneration.

9. Understory seedlings often become established under intensively managed young stands in the coastal hemlock-spruce type. When they do,.broadcast burning as a postlogging treatment should be avoided and the seedlings protected and utilized for the new timber crop.

1.0. Some mixed conifer stands have a heavy brush understory which becomes intermixed with logging residues after the stand is harvested. Broadcast burning is generally indicated here for controlling brush, reducing hazard, and opening the area for establishment of tree seedlings.

11. llistletoe-infected seedlings may be classed as forest residues and should be destroyed by broadcast burning or other methods as part of a disease control program.

12. West-side mixed conifer forests include a wide range of forest residue situations to which blanket rules seldom apply. The treatment for each area should be decided on the basis of local conditions, the favorable and unfavorable effects on regeneration and growth of the timber stand, and all the other factors appropriate to that site.

13. The downward trend in residue treatment by broadcast burning will continue as utilization standards improve and harvesting operations shift from defective old-growth to intensively managed young-growth forests.

RESEARCH NEEDED

An urgent research need in west-side mixed conifers is development of residue treatment techniques that will protect intermixed tree seedlings. The problem arises in two situations: first, advanced regeneration under overmature stands, and second, overstory removal as part of the shelterwood system. In the first instance, residue volumes may be very high and understory seedlings variable in size and distribution. In the second, residue volumes should be less because the stands will average younger and harvesting will be in two or more stages. Seedlings should be more plentiful and better distributed because the objective of shelterwood cutting is to create an environment favoring seedling establishment. In both situations, if the residues must be treated, the problem is to leave a full stocking of well-distributed seedlings.

A related research need is for development of residue treatment techniques for steep slopes. Sometimes intermixed seedlings need protection, sometimes not. If an overstory timber stand is present, a light mantle of duff and fine residues will protect the soil from erosion.

Only limited attention has been given to residues from precommercial and commercial thinning, perhaps rightfully so because regeneration is not directly involved in the early stages of stand development. However, commercial thinnings made toward the end of a rotation indeed do result in seedling establishment. To this extent they may be regarded as initial cuts under the shelterwood system. However the cuttings may be classified, the resulting residues need to be evaluated as to fire hazard, effect on growth, and in the case of late thinnings, effect on regeneration.

Soil compaction and root damage also need research attention. Shelterwood cutting and thinning operations involve operation of equipment over the soil surface with resulting compression of the soil and disturbance of root systems. The impact of this on the soil and tree roots needs careful investigation. Damage to the roots provides entry for disease which may affect tree growth and windthrow and may carry over to the next rotation.

NEEDS FOR EQUIPMENT DEVELOPMENT

Equipment is needed for better residue treatment with less damage to intermixed seedlings and the soil. This problem occurs on gentle slopes and steep slopes and with and without a residual overstory.

RESEARCH UNDERWAY

At present, no studies are underway dealing with effects of residue treatments on regeneration and growth of west-side mixed conifers.

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NATURAL REGENERATION OF EAST-SIDE CONIFER FORESTS

K.W. Seidel

ABSTRACT

Favorable and unfavorable effects of forest residues and their treatment on natural regeneration of the coniferous forests of eastern Oregon and Washington are discussed. The effects of burning and mechanical residue treatments on soil, seedlings, and advance reproduction are discussed in relation to natural stands, thinning operations, and selection, shelter-mod, and clearcutting regeneration systems.

*Although much additional **work** is needed to determine the relationships between residue treatments and regeneration in east-side forests, available evidence clearly indicates that a light amount of residue protects seedlings against environmental extremes and that complete residue removal or destruction is neither necessary nor desirable. When planning residue treatments, land managers should consider them not only as a means of fire hazard reduction but also as a method of improving the conditions needed for obtaining natural regeneration.*

Keywords: Mixed conifer forest (Pacific Northwest east side)--site preparation, natural regeneration, tree growth.

INTRODUCTION

As a forest stand develops from the seedling stage to maturity, residues accumulate on the forest floor as a result of leaf fall and from competitive tree mortality and mortality caused by insect or disease attacks. In addition to the natural buildup of residues, residues 'are added to the forest ecosystem by man's activities--thinning and other logging operations. In the coniferous forests of eastern Oregon and Washington, residues remain intact for many years because the dry climate **slows** the rate of decomposition. Because of their persistence, logging residues generally need treatment to reduce their fire hazard. Persisting residues are particularly troublesome in young pine stands that have been thinned. In addition to causing slow residue decay rates, east-side weather conditions often are unfavorable to seed germination and seedling establishment because of frost in the spring and heat damage in the summer.

The residues produced during the lifespan of a forest stand and the treatment of these residues will modify the microclimate, soil, and veqetation of the area and thereby have an effect on natural tree regeneration.

The purpose of this paper is to summarize the existing knowledge of residues and residue treatments on natural regeneration in eastern Oregon and Washington coniferous forests and adjacent areas having similar forest types. Only dead natural and manmade residues (snags, logging slash, litter, and duff) are considered here. Effects of living residues (brush and herbs) and their treatment are discussed by Gratkowski (1974).

DESCRIPTION OF FOREST TYPES

For purposes of this report, the coniferous forests of eastern Oregon and Washington are divided into two types: (1) the pine type which includes pure stands of climax ponderosa and lodgepole pine as well as mixtures of the two species and (2) the mixed conifer type. The mixed conifer type includes the *Pseudotsuga menziesii* Zone, *Abies grandis* Zone, and *Abies Zasiocarpa* Zone as described by Franklin and Dyrness (1969). The major species in this type are ponderosa pine *(Pinus ponderosa* Laws.), lodgepole pine (*P. contorta* Dougl.), western larch (*Larix occidentalis* Nutt.), grand fir *(Abies grandis* (Dougl.) Lindl.), white fir *(A. concolor* (Gord. & Glend.) Lindl.), subalpine fir *(A. Zasiocarpa* (Hook.) Nutt.), Engelmann spruce *(Picea engelmannii* Parry ex Engelm.), mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.), and Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco).

The stand structure and species composition of these forests are extremely variable, depending upon site, logging history, insect and disease attacks, and wildfire. As a result of past fires, the present forests are generally a mosaic of even-aged stands (or at least two- or three-aged), with even-aged overstories and one or two age classes in the understory. At lower elevations, mixtures of ponderosa pine and Douglas-fir are common. Farther up the slope, larch and lodgepole pine, both seral[1/] species in this type, are found in pure or mixed stands as a result of fire or clearcutting. In many such stands, an understory of Douglas-fir or grand fir is commonly found. At higher elevations, mountain hemlock and subalpine fir compose the climax vegetation.

Lodgepole pine is seral in the forests of eastern Oregon and Washington except on the pumice plateau of central Oregon, where it is found in pure stands in the pine type and is considered an edaphic or topoedaphic climax[2/] because of its ability to survive on more severe sites where there is little competition and temperature extremes are common.

[1/] Species in the early or developmental stages of a plant community before the climax or equilibrium condition.

[2/] Edaphic climax: a plant community that differs from the normal climatic climax because of abnormal soil conditions. Topoedaphic climax: a plant community that differs from the normal climatic climax because of abnormal soil conditions and special microclimates resulting from local topography.

Considerable variation exists in the forest soils of eastern Oregon and Washington. Most of them show the strong influence of volcanic activity, with varying amounts of ash or pumice incorporated into the horizons or deposited as thick layers on the surface. The most common great soil group in the eastern Oregon Cascades and Blue Mountains is the Western Brown Forest. This soil is found at the lower elevations in the forest-grassland transition zone and supports open stands of ponderosa pine or mixed ponderosa pine-Douglas-fir forests. With increasing elevation and a cooler; moister environment, Gray Wooded and Brown Podzolic soils are the dominant great soil groups. In the Blue Mountain region, regosolic soils with A-C profile sequences are widespread. These are young soils developed from pumicite and are found over older buried soils or basalt and support dense mixed conifer stands. In the pumice plateau area of south-central Oregon, the soils are Regosols developed from aerially deposited pumice ejected from Mount Mazama (Crater Lake) about 6,500 years ago. These soils have an A1-AC-C horizon development over the old buried soil, are occupied by pure climax lodgepole and ponderosa pine stands, and are low in fertility. The forest soils of eastern Washington show the same general pattern as in eastern Oregon. In the southeastern Washington Cascades, at the lower elevations, Western Brown Forest soils occur, along with Gray Wooded soils as elevation increases. In the northeastern Cascades, podzolization becomes increasingly important, and Brown Podzolic and Podzols are the major soil groups. Soil acidity increases with elevation; Western Brown Forest soils have the highest pH, and Podzols the lowest.

AMOUNTS OF RESIDUES PRESENT

The amount of residues in a given stand depends on the species composition, age, site, number of fires, and logging history. No information is available on the amount of litter and duff residues in stands of various ages and species in this area although Tarrant et al. (1951) reported on the annual litter fall of major tree species in the Pacific Northwest. On a dry weight basis, pure stands of ponderosa and lodgepole pine produced the smallest amount of litter. More research is needed to determine the rate of residue buildup and decay in natural stands.

Available data on residue amounts are limited to residues remaining after logging operations. In general, more residues result from logging in the mixed conifer type than in the pine type because of denser stands and more unmerchantable material in the mixed conifer type. In the pine type, Munger and Westveld (1931) reported that the volume of piled slash less than 4 inches (10.2 cm) in diameter ranged from 2,500 to 3,300 ft^3/acre (175 to 230 m^3/ha) after commercial logging which varied from partial cutting to clearcuttin?. They also found the volume of Douglas-fir slash to be two to three times that of pine slash in a similar stand.

Another survey in eastern Washington found an average of 112 ft^3/acre (8 m^3/ha) of sound bole wood larger than 4 inches (10.2 cm) in diameter in the pine type after commercial logging and 286 ft^3/acre (20 m^3/ha) in the mixed conifer type (Anonymous 1950). In this survey, the total amount of *sound* unused wood left in the forest was estimated at 6,168,000 ft^3 (174,680 m^3) for a five-county area. In a later survey using the same standards, Howard (1971) estimated that in 1969 an average of 325 ft^3/acre (23 m^3/ha) of usable wood fiber was left on National Forest land in the pine type of eastern Oregon and Washington after logging (clearcutting and partial cutting), and a total volume of 93 million ft^3 (2.63 million m^3) of usable residue on all ownerships in the pine type. In Idaho, Wilson et al. (1970) estimated that about 12 percent of the net cubic volume of trees to a 4-inch (10.2-cm) top was left as residue after logging in pine and mixed conifer stands.

Clearcutting in mixed conifer stands produces large amounts of slash. In a mixed conifer s'tand in northern Montana, Brown (1970) estimated the total dry weight of slash of all sizes to be 118 tons per acre (264 metric tons/ha).

Precommercial thinnings in overstocked pine stands also create considerable amounts of slash, especially at the wider spacings now recommended. Fahnestock (1968) estimated the total ovendry weight of slash created by thinning ponderosa pine stands to range from 1 to 19 tons per acre (2 to 43 metric tons/ha) at an 8- by 8-ft (2.4 by 2.4 m) spacing and from 14 to 40 tons per acre (31 to 90 metric tons/ha) at an 18- by 18-ft (5.5- by 5.5-m) spacing depending on age and site. He also reported that actual slash yields from thinning plots on the Deschutes National Forest were greater than the slash yield table estimates because of the greater stand density of the Deschutes plots.

The large amounts of slash created by such thinnings in both ponderosa and lodgepole pine stands remain intact on the ground for many years because of slow rates of decay and result in an extremely high fire hazard (fig. 1). Residue created by precommercial thi'nnings in east-side pine stands is a serious fire control problem, and the problem is growing as more acres of young stands are thinned each year because of intensified forest management.

UTILIZATION OF POTENTIAL RESIDUES

The best way to eliminate or greatly reduce the problem of residue disposal is, of course, to utilize the potential residue. Increased utilization depends primarily on the availability of markets for wood fiber and the economic feasibility of handling the residue. In eastern Oregon and Washington, the problem of utilizing logging residues is magnified because the markets for wood are not as diversified as on the west side: 80 percent of the mills are sawmills (Manock et al. 1970). Furthermore, pulp and fiberboard mills obtain nearly all their raw material as chips and shavings from sawmill residue; only 75 percent of this residue is now used (Wall et al. 1966). Thus, in eastern Oregon and Washington there is little demand for logging residue, but a tremendous supply is available. For example, in the ponderosa pine type of eastern Oregon alone, an estimated 57,160,000 ft3 (1,618,600 m^3) of usable logging residue was in the woods in 1969.[3/]

Converting this to weight by assuming the average dry weight of ponderosa pine to be 25 lb/ft^3 (0.403 g/cm^3) results in 714,500 tons (648,051 metric tons) of residue. According to Manock et al. (1970), the total capacity of all particle board and hardboard mills in eastern Oregon is about 845 tons (766 metric tons) per day. At this rate of consumption, enough unused logging residues remained in the woods in 1969 to furnish a continuous supply of raw material to these mills for a little over 3 years although rot and stain limitations prevented complete use of this material.

3/ Personal communication from James Howard, Resource Analyst, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

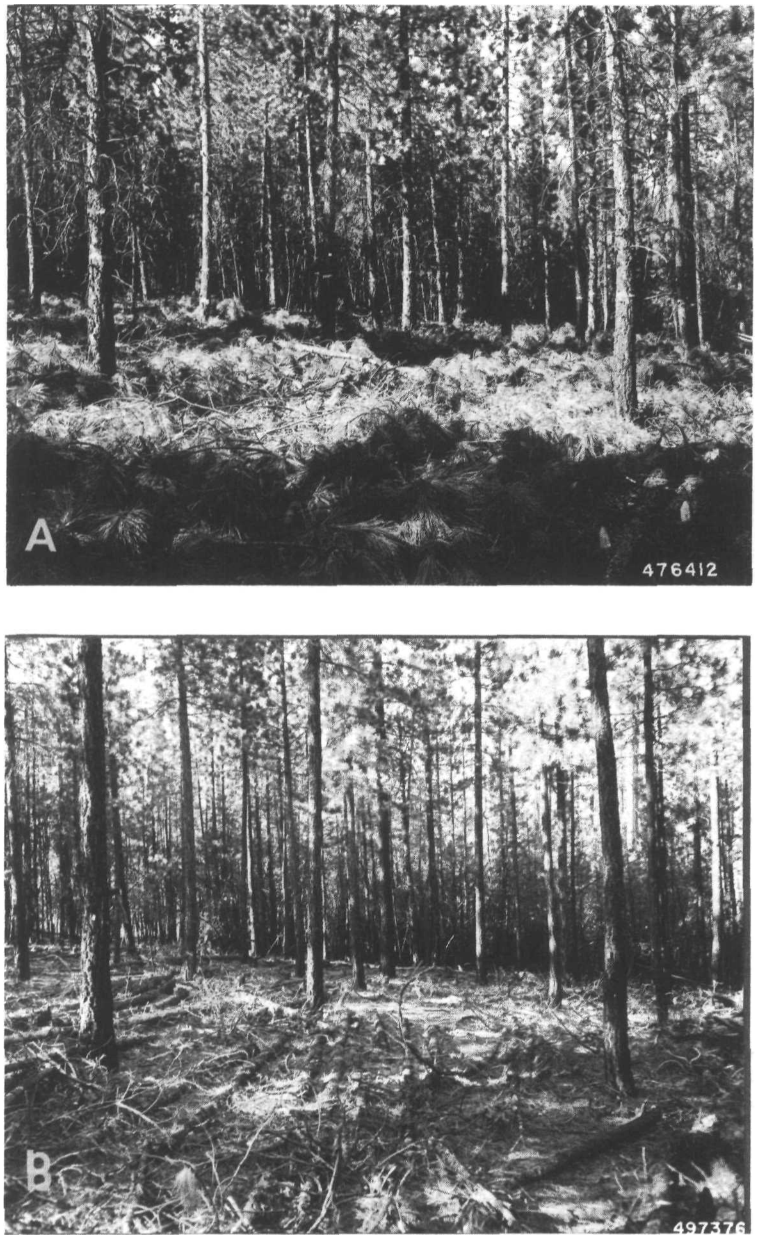

*Figure 1.—Slash resulting from precommercial thinning of a ponderosa pine stand to a 17- by 17-ft (5.2- by 5.2-m) spacing on the Deschutes National Forest: A, Immediately after thinning—fuel-rating is extreme-high; B, 7 years after thinning-needles have fallen but small branches are still intact—*fuel *rating is nowhigh-medium.*

Although the abundant supply of forest residues often causes disposal problems, it also presents opportunities for utilization of this material by creation of new markets or more efficient milling techniques. A good example of this is the utilization of large beetle-killed ponderosa pine trees in which the wood is still sound but honeycombed with beetle galleries and colored by blue stain fungus. These logs are sawn into boards by Brooks-Scanlon, Inc., for use as interior paneling or exterior siding. This corporation annually converts about 8 million board feet of pine snags and down trees into.a useful product which otherwise would be contributing to the residue problem.—

4/ Personal communication from Jay Gruenfeld, formerly Raw Materials Manager, Brooks-Scanlon, Inc., Bend, Oregon.

Another example of increased utilization by Erooks-Scanlon is the construction of a sawmill designed to handle small pine logs harvested in thinning operations. This multiproduct, completely automated mill produces boards, studs, and chips from logs as small as 3 or 4 inches (7.6 or 10.2 cm) top diameter and has an output of about 45 million board feet of lumber per year.

Utilization of residue is often restricted by lack of equipment that can economically handle, process, and transport this material long distances. Development of such equipment and techniques is needed for more complete use of residues.

Although utilization is a desirable answer to the problem of excess residue, it is not always an economically feasible alternative. And complete utilization of all residue is not desirable.

FAVORABLE AND UNFAVORABLE EFFECTS OF RESIDUES ON REGENERATION

ON THE SOIL

Many soil benefits are associated with forest residues, both on the surface and incorporated in the soil as organic matter. A covering of slash protects the soil from erosion on steep slopes and reduces loss of soil moisture by evaporation. As the slash decays and becomes mixed with the soil, it returns nutrients and increases water infiltration rates, water-holding capacity, aeration, and the cation exchange capacity of the soil. All soils, regardless of texture, are improved by the addition of organic matter. In coarse textured soils, organic matter increases the cation exchange capacity, thus reducing the loss of cation fertilizers by leaching. Water retention is also increased. In fine textured soils, organic matter promotes structure formation, which results in better aeration and increased water penetration.

Although the incorporation of organic matter into the soil has many desirable effects, adding large amounts of woody materials low in nitrogen to the soil can result in a tempdrary nitrogen deficiency because of the buildup of microbes which use the nitrogen in their metabolism, thus temporarily reducing the amount available for plants. In precommercial thinning operations where trees are cut and left on the ground, the large amounts of slash created may possibly have a detrimental effect on tree growth because of nitrogen immobilization. However, in the pumice soil region of central Oregon, Cochran (1963) estimated that no nitrogen deficiency should result from thinning slash left on the soil surface. If slash were chipped and incorporated into the soil, a small temporary nitrogen shortage is possible.

Annual removal of all residue down to mineral soil can result in site deterioration. A study by Jemison (1943), in which all litter was removed annually from a shortleaf pine (*Pinus echinata* Mill.) stand in North Carolina, showed that after 12 years, diameter growth of trees in the 10- to 13-inch (25.4- to 33.0-cm) class was significantly slower on the raked plot. Although no research has been undertaken in eastern Oregon or Washington to study the effect of residue removal on soil properties or tree growth, a reasonable assumption is that such drastic residue treatment would result in a lowering of forest productivity in the long run especially on the young pumiceous regosolic soils of' central Oregon which are relatively infertile.

ON SEEDLINGS AND ADVANCE REPRODUCTION

The effects of residues on tree seedlings and advance reproduction should be considered in young stands and also in mature stands when regeneration cuttings are planned. When young, overstocked stands are thinned and new seedlings are not wanted, residues can be helpful in preventing regeneration, by occupying the seed bed, particularly at the wider spacings where reproduction is most likely to become established. However, the large amounts of slash produced at these wide spacings greatly increase the fire hazard, so treating the slash in some way to reduce this hazard is generally necessary.

Although seedling establishment is not wanted early in the life of a stand, it becomes increasingly important as the stand nears maturity. As pointed out by Munger and Westveld (1931) and Pearson and Marsh (1935), advance reproduction established a decade or two befo're logging is important in the formation of the new stand in the pine type. In eastern Oregon, Munger and Westveld (1931) found that 53 to 98 percent of the new stand was made up of advance reproduction. Not all areas have adequate advance reproduction, however, and on these areas measures must be taken to secure new seedling regeneration after logging. Thus, the land manager is concerned with the effect of residues (slash as well as litter and duff) on both established and subsequent reproduction.

The effects of residues on regeneration will depend on the species, site, and amount of residue. Generally, the seral species (pines and larch) require a more disturbed seed bed and more sunlight to reaenerate satisfactorily. Stark (1965), working in mixed conifer stands on the west slope of the Sierra Nevada, found that conditions most favorable for germination were not always the best for survival. For example, white fir germinated best in half shade on bare soil and in full sun in light litter. On the other hand, it survived best in dense shade with medium litter and on shaded bare soil. Sugar pine (*Pinus lambertiana* Dougl.) both germinated and-survived best in full sunlight on light litter.

Under east-side conditions of hot, dry summers and freezing temperatures during the period of seed germination in the spring, it is generally agreed that a moderate cover of slash is of considerable value in seedling establishment, not only for the more tolerant species but for the pines as well, for protection against both high and low temperature extremes. On the pumice soils of central Oregon, germination of ponderosa pine seed was twice as great on slash-covered plots as on those where the slash was piled and burned, and seedling survival after 3 years was 37 percent on the slash plots compared with 19 percent on the burned plots (Munger and Westveld 1931). Although suggesting that a slash cover had a beneficial effect on seedling survival, these results are not conclusive because greater mortality on the burned plots may have been caused by the detrimental effect of the fire on physical soil properties. In a recent study of factors affecting lodgepole pine germination and survival in central Oregon, in scarified areas germination and first-year survival were better with a light to moderate slash cover than with no slash (Cochran 1973). Pearson and Marsh (1935) also found that on bare, coarse textured soil in the Southwest, a moderate slash cover is favorable to pine reproduction. In the Blue Mountains of eastern Oregon, similar results have been reported by Garrison (1961); 7 years after logging, the only ponderosa pine seedlings that survived were associated with rodent workings, old forest debris, or logging skid trails where slash modified the microclimate. No seedlings were found on completely bare skid trails.

There is ample evidence that all seedlings of the more tolerant species in the mixed conifer forests require partial shade for survival. Working on a clearcut area in Idaho, Ryker and Potter (1970) found that first-year survival of shaded Douglas-fir seedlings was twice as great as survival of unshaded seedlings. In northern California, first-year survival of true fir seedlings on clearcuts was best on shaded mineral soil seed beds and in shaded areas with less than one-fourth inch of litter (Gordon 1970). This was attributed to lower surface temperatures on mineral soil. In a study of subalpine fir-Engelmann spruce regeneration on clearcut areas in northern Idaho, Roe and DeJarnette (1965) found mineral soil to be the best seed bed and recommended leaving enough slash on clearcuts to provide partial shade. Day (1963, 1964) also concluded that in subalpine fir-spruce stands in southern Alberta, Canada, moist and shaded environments were necessary for reproduction on both mineral soil and humus seed beds; in British Columbia, Smith (1955) reached similar conclusions.

Undesirable effects of forest residues can be caused by either too much or too little residue. A thick, heavy litter layer or heavy amounts of logging slash will prevent seeds from reaching a mineral soil seed bed where they can successfully germinate and survive, and seedlings of shade-tolerant species can die on exposed sites because of insufficient logaing residue. Of all species in the mixed conifer type, western larch is probably most adversely affected by heavy litter layers and deep shade. Studies on the regeneration requirements of this species in Montana by Roe (1952) and in Idaho by Boyd and Deitschman (1969) have shown the superiority of a mineral soil seed bed and adequate light. In the Montana study, the number of larch seedlings surviving on undisturbed forest floors increased from 62 per acre in the 0- to 20-percent sunlight class to 1,730 per acre in the 81- to 100-percent sunlight class. In the Idaho study, both burning and light scarification of clearcut areas after logging resulted in a 20-percent stocking of larch compared with 8 percent in the area receiving no site preparation other than that caused by the logging. Heavy scarification further increased stocking to 40 percent.

Lodgepole pine also regenerates best on disturbed seed beds and in the absence of heavy amounts of slash. In the Blue Mountains of northeastern Oregon, Trappe (1959) reported that in clearcut areas, almost twice as many seedlings were found on mineral soil as on undisturbed litter, and most of the seedlings were established in the open rather than under the protection of slash. In southwestern Plontana and eastern Idaho, Lotan (1964) concluded that thorough seed bed preparation greatly improved germination and first-year survival of lodgepole pine in clearcut areas.

Thus, germination of all species in the pine and mixed conifer types appears to be improved by seed bed disturbance resulting in exposure of some mineral soil and the elimination of thick litter layers. First-year seedling'survival of all species except larch and lodgepole pine is generally increased as a result of protection given by a light amount of logging slash. However, the response of lodgepole pine seedlings to logging slash is not uniform throughout eastern Oregon and Washington. In most of this region, where lodgepole pine occurs as a seral species in the mixed conifer forests, it regenerates satisfactorily after disturbances without overhead shade. On the other hand, in the pumice plateau area of central Oregon, where this species forms climax stands, a light amount of logging residue seems to have a favorable effect on seedling survival.

Heavy logging residue also may be detrimental to advance reproduction by smothering seedlings or small saplings or by bending or twisting saplings, causing deformities. On the other hand, if advance reproduction is plentiful, some seedling mortality as a result of heavy slash can be beneficial, since it will thin the overly dense reproduction. In their slash disposal study in eastern Oregon, Munger and Westveld (1931) concluded that in the pine type mortality or deformation of advance reproduction by slash is not serious because usually only a small part of a logged area is covered by heavy slash which causes the most damage. However, in dense mixed conifer stands, heavy concentrations of logging slash could cause destruction of much of the advance reproduction.

The effect of slash on growth of seedlings and advance reproduction has not been studied as extensively as slash effects on germination and survival. For both new and advance ponderosa pine seedlings, Munger and Westveld (1931) found slash had no effect on shoot growth. Although partial shade from a moderate amount of slash increases seedling survival by preventing direct heat injury, reduction of light intensity can result in reduced taproot growth and make the seedlings more susceptible to mortality from drought. This has been shown by Day (1963, 1964) for spruce and fir. Although taproot length increased as light intensity increased for both species in this study, shoot growth responded differently for each species. Shoot growth of subalpine fir showed the same pattern as root growth--proportional to amount of light. In contrast, shoot growth of spruce was best in light to medium shade and decreased in heavy shade and full sunlight.

EFFECTS OF RESIDUE TREATMENTS ON SOIL AND REGENERATION

Treatment of residues to promote regeneration of tree species should consist of reducing heavy amounts of litter and slash so that some mineral soil is exposed and partial shade is cast on the area. Complete residue removal or destruction is not desirable. Treatments of dead residue can be classified either as mechanical or burning or combinations of the two. As in most silvicultural decisions, the choice of method depends on many factors such as species, presence or absence of advance reproduction, slope, and economic considerations.

NATURAL RESIDUES

The inevitable treatment (other than normal decomposition) of natural residues that build up in unlogged stands and in wilderness areas is fire--either wildfire prescribed by nature or underburning prescribed by man. Fire was responsible for the perpetuation of many of the most valuable forest types of the United States, including larch and lodgepole stands in the mixed conifer type and the ponderosa pine and Douglas-fir forests of the Western United States. The exclusion of fire by man from these natural fire types is altering the ecology of these forests as a result of greater quantities of residue and gradual replacement of the intolerant species with the more shade-tolerant climax species.

The importance of fire in maintaining ponderosa pine and the effects of its exclusion have been documented by Weaver (1967). Historical records show that the virgin ponderosa pine forests were generally parklike, with a grass or low shrub forest floor, and free of excessive residue. This condition was maintained by periodic light ground fires which consumed the small amounts of grass, needles, and twigs, thereby preventing accumulations of large amounts of residue. Pine seedlings became established in small openings where groups of trees had been killed by lightning, windthrow, insects, or disease; the snags and down trees were gradually consumed by the light fires. By the time the grass on these burned seed beds could support another fire, many of the pine seedlings were large enough to survive the fire, and a natural thinning of the clumps of reproduction occurred, stimulating the growth of the survivors.

Although fire served to perpetuate the open ponderosa pine stands, exclusion of the frequent light surface fires has had detrimental effects. Residues formerly consumed now continued to accumulate. When conditions for germination and survival were favorable, dense thickets of pine regeneration became established, adding to the fuel supply. Eventually, when lightning fires started in these stands, catastrophic conflagrations resulted, completely destroying the forest. And if not destroyed by the severe fires, the ponderosa pine on the better sites, where it is a seral species, was gradually eliminated by the more shade tolerant species that fire had kept out.

The importance of restoring fire to forested lands such as natural areas, wilderness areas, and National Parks is now widely recognized, not only in ponderosa pine types but in high-elevation mixed conifer types as well. It is now the policy of the National Park Service to allow natural lightning-caused fires to burn in certain high-elevation zones in California to reduce fuel and to maintain the ecosystem in its natural state (Kilgore and Briggs 1972).

Although restoring fire to natural forested ecosystems has many benefits, the task is difficult. The longer fire has been excluded from an area the greater the accumulation of residue and the greater the possibility of destructive fires rather than the desirable low intensity ground fires. Much additional research is needed on fuel modification and prescribed burning techniques for the restoration of fire as a natural agent in western coniferous ecosystems.

THINNING RESIDUES

No treatment of thinning residues is needed as a means of securing regeneration, since no new seedlings are wanted at this time and large amounts of residue prevent seedling establishment. Therefore, treatment of thinning residues is a matter of reducing the fuel concentration to an acceptable level for fire control and of providing accessibility for future silvicultural operations.

On slopes not exceeding 25 to 30 percent, the use of heavy tractor-mounted equipment to crush, chop, shred, or masticate the slash is an effective treatment method as long as leave trees are far enough apart to allow tractor movement without damage. Three machines commonly used for this type of slash treatment are the "Tomahawk," the "Marden Brushcutter," and the "Tree Eater."

The Tomahawk (fig. 2) and the Marden Brushcutter were tested in slash from thinning of pine on the Deschutes National Forest in central Oregon by Dell and Ward (1969). Although their primary objective was to evaluate this equipment for reducing fire hazard, they found both machines did effective jobs of scarification in green slash--superior to crushing with a crawler tractor alone. The Marden had limited maneuverability resulting in scarred tree boles and some untreated slash left near leave trees.

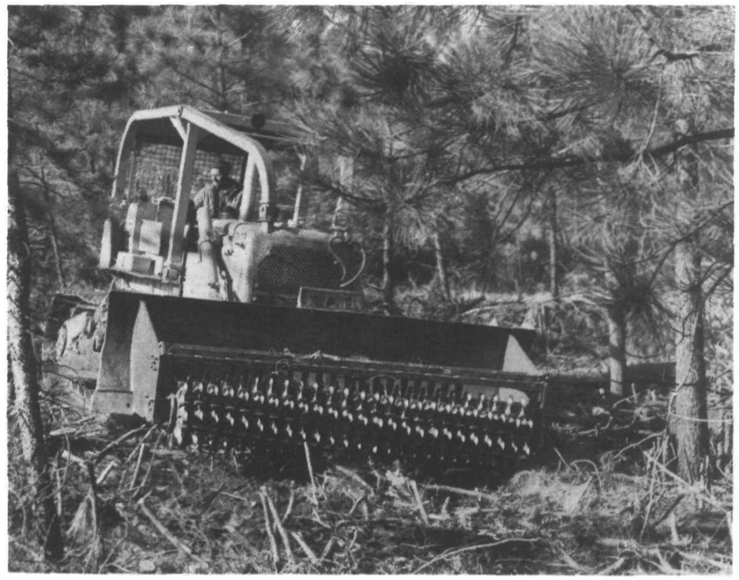

Figure 2.--Tomahawk crusher mounted on crawler tractor crushes slash from thinning of pines.

The Tree Eater consists of a front-end flail cutter mounted on a crawler tractor. The flail cutters rotate at 1,800 r/m and reduce all trees, shrubs, or slash to a mulch. Trials in the Southwest by Burbank et al. (1970) showed that the machine was able to thin a strip and masticate the slash on slopes of less than 20 percent. The Tree Eater has been tested in central Oregon for treating residues on areas to be planted (fig. 3). There the residues were reduced to a mulch that diminished soil moisture loss. Costs of this treatment were comparable to dozer piling and burning of slash.5/

Another method of handling thinning residues is with mechanical harvesters that remove the entire tree including the top from the logged area. Such machines ("Feller-Bunchers") have been tested in eastern Oregon by the Boise-Cascade Corporation in the mixed conifer type.6/

Clearcut strips about 25 ft (7.6 m) wide are alternated with strips about 50 ft (15.2 m) wide from which trees are to be harvested by the Feller-Buncher. The harvester then reaches in to the stand 25 ft (7.6 m) from the clearcut strips, cuts the trees at the stumps with shears, then removes the entire tree to the clearcut strip where it is piled. This machine can handle trees up to about 18-inch (45.7-cm) stump diameter and can be used for thinning or for removing an overstory from established reproduction with little damage to the advance

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5/ Personal communication from Julian Wojtowych, Forester, Deschutes National Forest.

6/ Personal communication from Glenn Parsons, Administrator, Northeast Oregon Lands, Boise-Cascade Corporation.

reproduction; e.g., removal of lodgepole pine overstory from true fir regeneration in the mixed conifer type. Increased utilization is another advantage. Since the entire tree has been brought to the landing, there is a tendency to use as much of the bole as possible' (depending on existing markets for small logs or pulpwood).

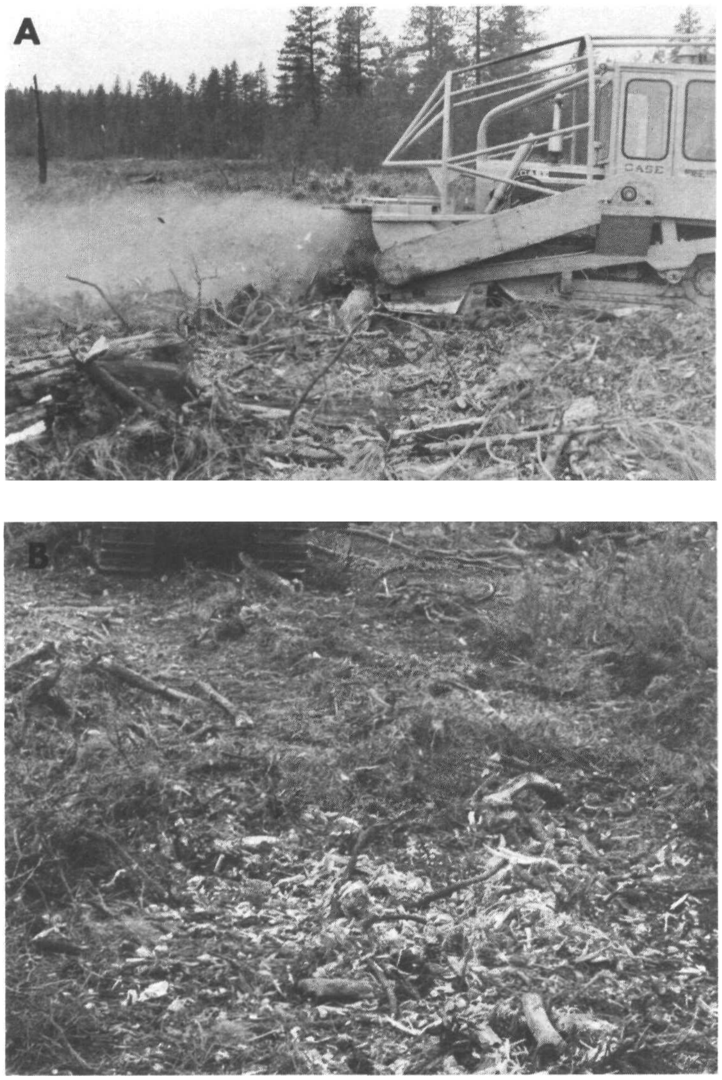

Figure 3.--Tree Eater operation on Deschutes National Forest: A, Treating logging residue prior to planting seedlings: B, appearance of residue after treatment.

SELECTION SYSTEM RESIDUES

When logging residues produced as a result of management under the selection system are treated, advance reproduction and the existing stand of growing stock must be protected. On the Warm Springs Indian Reservation in central Oregon, the single-tree selection system is used for management of ponderosa pine stands.

Logging slash is piled to be burned when there is little wind to spread fire to surrounding trees. This treatment provides a more receptive seed bed for establishment of new seedlings by consuming litter, grass, and shrubs.[7/]

Prescribed light underburning for thinning purposes has been studied by Weaver (1946) in selectively cut ponderosa pine stands in eastern Washington. He concluded that there was little damage to the residual stand or advance reproduction and that dense clumps of reproduction were thinned by the fire resulting in faster growth of the survivors. Later remeasurement of his study by Morris and Mowat (1958) confirmed the better growth of trees on the burned plots; diameter growth was 36 percent greater and height growth 7 percent greater. Although the use of fire to thin dense clumps of pine reproduction is economical and gave satisfactory results in this case, prescribed burning is a crude and imperfect thinning tool when intensive forest management is practiced because results are not predictable. For example, in another study in the same general area in eastern Washington, Wooldridge and Weaver (1965) found that both diameter growth and height growth were less on the burned plots than on the unburned plots after 6 years.

In addition to causing erratic growth responses, fire does not thin stands uniformly. In some places, clumps of unthinned trees may remain, but all regeneration might be destroyed in poorly stocked areas. Gordon (1967) concluded that, in northeastern California ponderosa pine stands, underburning would almost completely kill pine seedling and sapling groups which were most in need of thinning and thereby add to the fuel supply. Likewise, in a study of the effects of underburning in selectively cut ponderosa pine stands in Arizona, Lindenmuth (1960) found that for every potential crop tree released, an average of five potential crop trees needed to utilize growing space were damaged or killed. These examples indicate a need for great care in prescribing and producing the proper intensity of fire to do the job.

SHELTERWOOD SYSTEM RESIDUES

Treatment of logging residues left by the shelterwood system depends upon the stage of cutting. If no reproduction is present or existing reproduction is mistletoe infected, and the logging operation is the initial cut in a two-stage shelterwood system, then most methods of residue treatment are suitable as long as damage to the residual trees is avoided. In both the pine and mixed conifer types, where slopes permit, heavy equipment can be used to crush or shred the slash. For best results, this treatment should be used in conjunction with tree-length logging to a 4-inch (10.2-cm) top diameter or yarding of unutilized material (YUM) since larger material is not effectively broken.[8/]

Alternative methods are to yard all unmerchantable material and machine pile the remaining slash, with or without burning, or to pile and burn all residue.

7/ Personal communication from Gunther Heeren, Supervisory Forester, Warm Springs Indian Reservation, Bureau of Indian Affairs.

8/ Proposed revision of Region 6 slash treatment guidelines by D. Franks and W. Shenk, Fire Control, Deschutes National Forest.

Care must be taken to pile residue far enough from residual trees to prevent scorching when piles are burned.

Prescribed burning of logging slash after shelterwood cuttings is not recommended because the residual trees are likely to be damaged by the fire, especially in mixed conifer stands where low-hanging branches can carry the fire into the crown.

Although possible fire damage to residual trees makes prescribed area burning of logging slash after shelterwood cuttings impractical, preparation of seed beds by light burning is feasible under mature, managed ponderosa pine stands lacking reproduction and logging slash. The objective of the burn would be to consume most of the litter and duff and to kill back brush and herbs without generating enough heat to damage tree crowns and lose seed production. Considerable research and experience are needed to determine the optimum combinations of weather and fuel conditions for this objective.

Skidding of the entire tree to landings is another possible method of handling logging residues both in shelterwood cuttings and in clearcut areas where tree size permits. This method removes slash for disposal at the landing and provides seed bed scarification at the same time. Although these are advantages, unfavorable effects can also occur. When seedlings require the protection of a light slash cover, removal of all logging residue can result in greater seedling mortality; complete tree removal may also deplete soil nuturients in. the long run.

All treatments of residue by machines are limited to terrain with slopes of less than 30 percent. On steeper ground, slash can be lopped and scattered by hand to reduce the fire hazard if amounts are not excessive. Little seed bed improvement would be expected from this treatment since the forest floor is not disturbed to any extent. However, Gordon (1970) found that lopping and scattering logging slash in the true fir type in California resulted in a greater number of seedlings per milacre (0.0004 hectare) than no slash treatment. There was no apparent reason for the better regeneration since he reported a uniform distribution of a deep layer of organic fines in the lop and scatter treatment.

Treatment of residues resulting from the final cut in a shelterwood system (overstory removal) should be done in a manner which causes the least damage to the established reproduction. On gentle slopes, equipment such as front-end loaders can be used to remove residues from the logged areas for disposal elsewhere or to pile residues for burning. Such equipment can lift tops off the ground and use existing skid trails to minimize damage to existing reproduction. There is a good opportunity here to develop and test new equipment which effectively handles logging residues while protecting the reproduction.

Use of heavy machines for residue treatments raises the possibility of soil compaction and reduced infiltration rates. In western Montana, Tackle (1962) found that soil compaction created by piling larch-Douglas-fir slash and scarifying the seed bed with a tractor reduced infiltration by 85 percent the first year after logging on 55 percent of the area. After 5 years, infiltration on the scarified area was still only about 45 percent of the control. The soil in the study area was a silty clay loam. In coarser textured soils, such as in the pumice region of central Oregon, less compaction probably would occur; but this has not been studied.

For seedling establishment the favorable effects of residue treatment by mechanical methods and by burning are generally recognized and accepted. Surprisingly, there is no documentation of the effects of such treatments in conjunction with shelterwood cuttings in eastern Oregon and Washington. Research is needed to study the relationships between cutting intensity, slash treatments, and regeneration on various sites in both the pine and mixed conifer types.

CLEARCUT SYSTEM RESIDUES

Clearcutting creates the greatest amounts of residue and also permits the greatest flexibility in choice of residue treatments. Under current practice, any method suitable for the terrain may be used since no constraints are imposed by residual overstory. Although advance reproduction will usually be present to some extent, the logging operation and subsequent slash treatment may destroy or damage much of it. And on some areas, it may be necessary to eliminate the advance reproduction because of mistletoe infection or inability to respond to release. As a result, either natural seeding or planting is depended upon to establish the new stand. Because there is no overstory to protect seedlings against temperature extremes, some residue should be left on clearcuts for this purpose, especially for natural regeneration of the more tolerant true firs and mountain hemlock.

The most common method of residue treatment after clearcutting is to machine pile and burn. This method has the favorable effect of scarifying the forest floor, thus preparing a receptive seed bed for seedling establishment, but complete residue removal can result in increased mortality of tolerant species. Scarification is effective in site preparation. In British Columbia, Smith (1955) reported 188,500 spruce seedlings and 5,000 subalpine fir seedlings per acre on scarified seed beds compared with only 682 spruce and 86 fir seedlings per acre on the undisturbed area after a bumper seed year.

In the Intermountain Region, Roe et al. (1970) concluded that mechanically exposed mineral soil was superior to other types of seed bed for spruce seedling establishment and early survival. They also stressed the point mentioned previously that, although scarification should expose some mineral soil and eliminate competing vegetation, some slash should be left for shade and to prevent soil erosion. On erodible soils, they recommended tractor scarification of alternate strips. Some residue was then pushed back on the strips and the dozer walked over it at right angles to the strips, breaking down the residue.

Although residue treatment by piling and burning creates favorable seed beds by scarification, burning of the slash piles can also result in extremely hot fires that bake the soil causing conditions detrimental to conifer reproduction. In Montana, burning of piled slash on clearcut areas in the mixed conifer type resulted in 80-percent-less reproduction on the burned areas than on adjacent unburned sites (Vogl and Ryder 1969). Furthermore, the inhibitory effect of the severe burns on conifer reproduction lasted for at least 15 years. The soil was a Brown Podzolic. Vogl and Ryder attributed the poor stocking on the burned areas to a laminated surface crust consisting of bits and chunks of charcoal and suggested broadcast burning to avoid soil damage. Apparently, on the coarser textured soils of central Oregon, burning of piled slash does not cause significant damage, but more research is needed.

An interesting modification of the pile and burn method has been tested in California by Schimke and Dougherty (1967); a portable metal bin was used to burn the slash. This method has several advantages over the standard burning of piles in the open: soil damage is avoided, little smoke is emitted because of the high temperatures, burning of green or wet slash is possible, few spot fires occur, and putting lines around many piles and patrolling them is not necessary. Costs of this method were comparable with other slash disposal treatments.

Burying of logging slash in pits or trenches is another method of eliminating the residue and obtaining seed bed scarification at the same time (fig. 4). Schimke and Dougherty (1966) tested several methods of burying slash in central California and concluded that they were feasible in areas that were not rocky or too steep for operation of equipment. At higher elevations in the mixed conifer type, burning of slash in the fall is often prevented by early snows, and slash can be buried. Burying is also useful for slash disposal in areas in which esthetic considerations prevent other residue treatment methods. Although burying the residue effectively removes it from the area, its incorporation into the soil could result in nitrogen immobilization and reduce growth of new reproduction. This aspect of slash treatment on regeneration has not yet been studied in east-side forests. Disruption of the soil profile could also result in loss of nutrients by leaching if upper horizons are deeply buried beyond the root zone of young seedlings. When residue is buried, an effort should be made to replace upper soil horizons at the surface.

Broadcast burning can be an effective seed bed preparation method in clear-cut areas since this is nature's way of regenerating the pioneer fire species--such as larch and lodgepole pine--by exposing mineral soil and destroying competing vegetation. In practice, however, results are likely to be highly variable because of differences in fire intensity due to variations in fuel quantity and weather conditions. As pointed out by Roe et al. (1970), timing of broadcast burning is especially critical in the high-elevation mixed conifer type. The time available for burning is very limited since both high fire danger in the summer and early rains or snow in the fall prevent burning. They emphasize that the key to obtaining a successful broadcast burn is the moisture content of the duff. If it is too wet to burn and only the surface layer is consumed, a blackened organic layer that prevents seedling establishment will remain. More research is needed to determine optimum weather and fuel condtions for broadcast burning.

The effects of burning on physical and chemical soil properties and subsequent seedling establishment and growth vary because of the many factors influencing the results. Tarrant (1956a, 1956b) studied the effect of prescribed burning on soil physical properties in both eastern and western' Oregon and Washington. He concluded that no soil damage resulted from light surface burns; but severe burning, in which all organic matter was consumed and the mineral soil was colored, resulted in a reduction to 30 percent in the water percolation rate of the unburned soil. On broadcast burned areas, however, usually only a small amount of the area (< 5 percent) is severely burned.

Similarly in their Montana burning study, Vogl and Ryder (1969) reported that water was absorbed into the soil 4.6 times more slowly in the severely burned areas than in the unburned soil and that even 15 years after burning, infiltration was still slower on the burned soil.

Figure 4.—Burying logging slash created by thinning of a pine stand in a landscape management unit: A, Slash being pushed into trench; B, after all slash is in trench; C, area covered with soil.

Generally, the effect of fire on soil chemical properties is favorable. Amounts of available phosphorus, potassium, calcium, and magnesium are increased by the ash deposit from the fire, and the alkaline ash decreases soil acidity (Vogl and Ryder 1969, Tarrant 1954, Vlamis et al. 1955). Burning results in a loss of nitrogen from the forest floor, but nitrification in the soil is stimulated by the increased alkalinity. A study of prescribed burning in ponderosa pine forests in California by Klemmedson et al. (1962) showed that a combination of broadcast burning and burning of piled slash resulted in a loss of 69 percent of the nitrogen from the forest floor. The soil was a Salminas loam. Despite this loss of nitrogen from organic matter, they found a net gain of total soil nitrogen in the first inch (2.5 cm) of soil after 18 months and concluded this was caused by leaching of the decomposing forest floor remaining after the burn. Thus, seedling growth can be stimulated by the increased availability of soil nutrients, but there is also the possibility of increasing the growth of brush and herbs which hinders tree seedling establishment because of heavy competition for soil moisture.

Another unfavorable effect of burning on forest soils in some areas is the creation of "nonwettable" soil which inhibits natural regeneration on the area. This is not the ordinary reduction in infiltration from deterioration of physical properties by severe fires but the formation of a water-repellent layer consisting of a hydrophobic organic coating on the soil particles (Krammes and DeBano 1965, DeBano et al. 1970). This condition occurs most commonly in southern California in the chaparral type where some organic component of the chaparral litter is thought to make the soil hydrophobic. Water repellency in soils has also been studied in Montana by DeByle and Packer (1970). They measured degree of water repellency of the soil before and after burning of slash in the larch-fir type and concluded that wettability was more closely related to soil depth and aspect than to burning, with fewer than one-third of all the soil samples being difficult to wet after burning. This condition has been observed in the Oregon Cascades (unpublished study) where the soil remained "nonwettable" for several years after a wildfire. Further work is needed to determine the extent of this problem in eastern Oregon and Washington soil types.

Broadcast burning can be a useful tool for seed bed preparation if done when conditions are suitable. Generally, little or no soil damage would result since high temperatures are not concentrated on one spot for long periods, and no soil compaction by heavy equipment would occur. Broadcast burning is restricted to short periods when weather conditions are favorable in the high-elevation mixed conifer type. It is more useful in the pine type because a longer snow-free period results in more days when burning conditions are likely to be favorable. Burning of piled residue has the advantage of the forest floor being scarified when piling is done by machine, and there is less chance of the fire escaping. On the other hand, if the piles of slash occupy a significant portion of the area and burning conditions result in extremely hot fires, adequate regeneration may not be obtained because of impairment of physical soil properties. In this case, disposal of residue in portable incinerators would eliminate the possibility of soil damage.

Chipping of logging residue on clearcut areas by portable chipper is another slash treatment (fig. 5). In east-side forests where residue decay is slow, this method would speed the return of nutrients to the soil by increasing decomposition rates and would lower the fire hazard, but it might also result in a temporary shortage of soil nitrogen., In addition, a thick layer of chips on the soil surface could result in a poor seed bed. Although this is an unfavorable effect

Figure 5.--Chipping logging slash on the Deschutes National Forest. Chipper is being used here to dispose of slash from a thinning, but equipment could also be used in clearcut areas.

in most cases, under certain conditions it could be desirable. For example, when favorable weather conditions for germination and survival combine with a bumper seed crop and a mineral soil seed bed, an overabundance of larch or lodgepole pine seedlings is often found on clearcuts in these species. Possibly such overstocking could be avoided by reducing the area of mineral soil with chipped residue. However, nothing is known about the effect of chipped slash on the soils or seedling establishment in east-side forests, and research is needed before any recommendations can be made. At present, it is wise to prepare the best possible seed bed on the assumption that seed supply and weather will be limiting factors.

CONCLUSIONS AND RECOMMENDATIONS

Much additional research is needed to determine the relationships between. residue treatments and regeneration and growth of tree species in both the pine and mixed conifer types of eastern Oregon and Washington. Early work in the field of residues has been mainly concerned with their treatment as a fire protection measure, with little attention given to effects on natural regeneration. Hawley and Smith (1954) summarized this situation:

> It is unfortunate that slash disposal has received far more attention as a means of fire protection than as a method of stimulating reproduction. This attitude has commonly led to the application of methods of slash disposal which are not compatible with the renewal of the forest. Generally speaking, the modifications of practice which would be beneficial to

reproduction lie in the direction of partial, rather than complete, disposal of slash.

Some important problems needing study are:

1. What amounts of residues are present in natural and managed stands in various types at different ages, and what is the rate of decay?

2. What kinds of residue treatments are most favorable for the establishment and growth of new seedlings after shelterwood cuttings of various intensities in pine and mixed conifer stands?

3. What are the best methods of treating residues created by removal of overstory to minimize damage to the advance reproduction?

4. What residue treatments are most beneficial for regeneration on clearcut areas, especially on severe sites such as the pumice plateau of central Oregon?

5. What is the effect of burying and chipping slash on soil nitrogen relationships and subsequent seedling establishment and growth?

6. What is the long-term effect of various residue treatments on forest productivity, particularly those methods which remove much of the residue from the area?

7. When is the best time to broadcast burn in terms of weather and fuel conditions to obtain optimum seed bed conditions on logged areas?

8. How can wildfire and prescribed burning best be used in natural stands and wilderness areas to prevent excessive residue buildup and to restore and maintain the normal ecosystem present before the exclusion of fire?

In the field of equipment development, there is always a need for new methods and machines for better residue treatment with less damage to soil or vegetation. Better equipment would be of value (1) to treat residues with less damage to reproduction and soil than at present in stands with advance reproduction and (2) to economically handle, modify, and transport residues for more efficient utilization.

Specific recommendations for residue treatments to favor natural regeneration in the pine and mixed conifer types of eastern Oregon and Washington based on documented research cannot be made at this time. However, from the work done in surrounding regions and from observations and experience, three general recommendations are suggested:

1. Land managers not only should consider residue treatment as a means of reducing fire hazard but also should consider the effects of such treatments on new regeneration and advance reproduction.

2. Land managers should create favorable seed beds for seedling establishment by eliminating thick litter layers and exposing some mineral soil. Complete destruction or removal of the forest floor is not desirable.

3. Land managers should keep in mind the importance of leaving some residue (logging slash) for protection of seedlings from temperature extremes.

This is extremely critical on clearcuts or sites where environmental conditions are unusually severe, and in regenerating spruce or the true firs.

RESEARCH UNDERWAY

At present, two studies are underway dealing with effects of residue treatments on natural regeneration in eastern Oregon. These studies are being conducted in Bend, Oregon, by a timber management research project of the Pacific Northwest Forest and Range Experiment Station. One deals with the problem of obtaining reproduction after shelterwood cuttings in mature true fir stands. It will consider the effect of several intensities of cutting and several methods of slash treatment on germination and survival of true fir seedlings. The second exploratory study is investigating underburning of litter and brush as a seed bed preparation in mature ponderosa pine stands.

Work on residue management is also being done by other Forest Service Experiment Stations. In Wyoming, the Intermountain Station is studying broadcast burning and chipping of logging residues after clearcutting mature lodgepole pine. This study is concerned with the effect of these treatments on regeneration, nutrient cycling, hydrology, and wood utilization. And in Montana, the Intermountain Station has begun a research and development program in the larch-Douglas-fir forests to study new methods of harvesting and handling residues. This is a multidisciplinary program involving the effects of various levels of residue utilization on regeneration, wildlife habitat, fuels, forest insects and fungi, hydrology, nutrient cycling, esthetics, and engineering.[9/]

In Colorado, the Rocky Mountain Forest and Range Experiment Station is studying natural regeneration of Engelmann spruce in clearcuts as affected by mechanical 'scarification of the seed bed.[10/]

Because research programs change with time, readers interested in current research in residue management should contact Forest Service Experiment Station headquarters for up-to-date information.

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ARTIFICIAL REGENERATION

James W. Edgren and William I. Stein

ABSTRACT

In the Pacific Northwest, planting and seeding currently constitute a high proportion of the Zarge reforestation effort. The presence or removal of woody residues accumulated during growth and harvest of the former stand has a strong influence on ease and success of artificial reforestation efforts. Residues affect restocking mechanically through obstruction of planters and occupation of surface area, and environmentally by alteration of the microsite climates in which seedlings must survive and grow. Knowledge avaiZable on these reZationships is reviewed, needed information identified, and direction of future research suggested.

Keywords: Artificial regeneration--seedling environment, site preparation, seedling growth.

Prompt regeneration of nonstocked forest land is essential for maximum sustained production of timber. Nonstocked lands may be restocked through natural regeneration; but to assure promptness, we often turn to direct seeding or planting. The presence or removal of woody residues accumulated during growth and harvest of the former stand has a strong influence on ease and success of artificial reforestation efforts. Residues affect restocking mechanically through obstruction of planters and occupation of surface area, and environmentally by alteration of the microsite climates in which seedlings must survive and grow.

Planting is now the favored reforestation method in Oregon and Washington. In fiscal year 1973, 278,447 acres (112,684 ha) were planted and 50,580 acres (20,469 ha) were direct seeded on public and private lands in the two States (USDA Forest Service 1973b). This represents a 39-percent increase in artificial reforestation acreage since fiscal year 1968 but a decrease in direct seeding from 40 to 15 percent of the total effort. In fiscal year 1973, 84,240 acres (34,091 ha) of National Forest lands were planted or seeded in Oregon and Washington; only 14,684 acres (5,942 ha). were reforested through natural regeneration (USDA Forest Service 1973a). Statewide totals for acreage restocked by natural regeneration are not available; although the proportion may be somewhat higher than on National Forest lands, natural regeneration now appears to constitute a minor part of total reforestation. It may become a larger proportion of the total as greater reliance is placed on shelterwood and seed-tree cuttings, but increased underplanting may offset part of the change in cutting method.

Artificial reforestation, particularly planting, provides several advantages over natural regeneration. Delay in restocking caused by poor seed years and seed depredation can be avoided, desired tree species can be favored readily, site conditions unfavorable to natural seedlings can be overcome, and tree distribution can be accurately controlled. Though usually more expensive than direct seeding, planting is favored because it permits a higher degree of stock and stand control, provides a higher yield from precious seed, allows efficient genetic upgrading of new stands, and often circumvents the slow field growth and development of tender young seedlings. Of course, the advantages of artificial reforestation accrue only if stands of suitable source and species are successfully established.

A brief overview of conifer seedling requirements for light, heat, moisture, and nutrients provides a necessary preamble to a discussion of residue-regeneration relationships. The diverse and fragmented evidence on these relationships is then covered in sections on mechanical and environmental effects of residues and residue treatments on seeded and planted trees. Salient engineering and biological research needed to improve both residue treatment and regeneration practice are discussed in the final section.

ENVIRONMENTAL FACTORS AND SEEDLING GROWTH

Light, temperature, moisture, and nutrients are generally the key environmental factors governing tree seedling establishment and growth. Seedlings will grow poorly or die if any one factor is seriously deficient or overly abundant. Seedling response to various combinations of these environmental factors differs as does the effect at different stages of development, and response also varies substantially by species. Thus, one cannot define a single set of environmental objectives or standards to be achieved when manaaing residues for the benefit of regeneration. How the environmental factors influence tree establishment and development has received indepth, yet incomplete, coverage in many publications, i.e., Baker 1950, Baule and Fricker 1970, Epstein 1972, Kramer 1969, Kramer and Kozlowski 1960, Kozlowski 1968, Levitt 1972, Romberger 1963, Spurr and Barnes 1973.

LIGHT

Intensity, quality, duration, and periodicity of light affect the growth of tree seedlings. Optimum light intensity for growth of many species is less than full sunlight. For example, redwood *(Sequoia sempervirens* (D. Don) Endl.) seedlings can grow rapidly if provided with radiant energy equivalent to 10 percent of full sunlight, but Douglas-fir ***(Pseudotsuga** rnenziesii* (Mirb.) Franco) and Engelmann spruce *(Picea engelmannii* Parry) require about twice as much for appreciable growth. Eastern white pine *(Pinus strobus* L.) produced maximum dry weight in 43 percent of full sun, red pine *(Pinus resinosa* Ait.) and white spruce *(Picea glauca* Iloench) Voss) in 98 percent. At high elevations, full sunlight may actually harm the hotosynthetic processes of sensitive species such as Engelmann spruce (Ronco 19737. More sunlight is needed for maximum growth as seedlings get older since limbs and needles shade each other.

Quality of light influences the gross morphology, anatomy, and carbohydrate content of tree seedlings. Though substantial differences can be produced under experimental conditions, variations in light quality which occur under natural conditions are generally not great enough to materially affect seedling growth.

However, location and nature of objects intercepting or filtering sunlight are critically important ih regulating the duration of exposure and total energy received. Seedlings of many tree species are also sensitive to day length, but the natural effects of these factors are an integral part of seedling response at different geographic locations.

TEMPERATURE

Moderate air and soil temperatures are best for the growth of tree seedlings. Extremes of either hot or cold often seriously injure or kill young seedlings and sometimes damage older seedlings and saplings. Succulent stems of many species are damaged near the ground line by contact with or radiation from intensely heated soil surfaces. The thermal death point for active, cells of many higher plants is between 45" and 65" C (113" and 149" F)--temperatures exceeded in the summer on exposed surfaces of numerous soils in the Pacific Northwest. Despite the common occurrence of lethal surface temperatures, the combined effect of moderating factors--such as age and size of seedling; species characteristics; soil surface color, texture, and moisture content; duration of exposure; cooling effect of transpiration and shading; and other influences--permit many seedlings to survive. Indirect sources of heat injury involve the acceleration of physiological processes as temperatures rise, the increasingly unfavorable balance between photosynthesis and respiration, and the desiccation which may accompany accelerated transpiration.

When fully hardened and located in a protected microsite, tree seedlings can tolerate low subfreezing temperatures without injury. But unhardened seedlings may be severely damaged or killed if exposed to temperatures only a few degrees below freezing. Seedling tops are more hardy than roots, but the latter benefit from soil protection. Tops of cold or frozen seedlings may desiccate from overexposure to wind or sun, and alternate freezing and thawing in exposed locations may tear seedlings loose and lift them from the soil. The physical location of the seedling and the timing of low temperatures relative to stage of seedling development are key factors governing degree of physical damage. Below normal air or soil temperatures during the growing season slow the usual rate of growth.

MOISTURE

Seedlings of woody plants grow best when there is little or no soil water stress. Stem elongation and dry weight production may be adversely affected by as little as 0.5-bar reduction in water potential. Growth may be reduced substantially when seedlings experience soil water potentials of -2 to -4 bars. It is now generally agreed that as soil moisture content decreases, water becomes progressively less available; but there is no definite point at which it becomes unavailable to plants (Kramer 1969).

Soil and plant water stresses are often correlated, but they are not synonymous. Plant growth is controlled directly by internal water stress and only indirectly by soil water stress. The relative rates of water absorption and transpiration govern the plant's internal water balance; thus, its water stress is the product of both soil and atmospheric moisture conditions. Plant water stress sufficient to cause injury may develop under conditions of high transpiration even when moisture content of soil is substantial. Most desiccation injury results, however, from plant water stress which develops because of a decreasing supply of soil moisture.

Overly abundant soil moisture can also be damaging to tree seedlings. Many species are injured or killed by more than temporary flooding. Excessively wet soils lack the aeration necessary for good development of most roots. Aeration may be impaired by flooding, poor drainage, or soil compaction.

NUTRIENTS

Tree seedlings require the same nutrient elements needed for the healthy growth of all plants. As with other plants, a balanced nutrient supply is required in which each nutrient is present in a suitable range of quantities relative to the concentration of other nutrients. Species differ in their nutrient requirements; optimum levels still need to be determined for most tree species.

Trees sustain satisfactory growth on relatively low quantities of nutrients, provided primarily by the weathering of soil minerals and the mineralization of atmospheric nitrogen. A substantial portion of the nutrients used by trees recycles through the decomposition of vegetation and incorporation of organic matter into the soil. Many soil organisms assist in these processes. Symbiotic relationships which seedling roots form with various mycorrhizal fungi play a key roll in nutrition, water uptake, and protection from disease. The kind of soil, its geographic location, degree of exposure to varying climatic influences, organisms present, and many other factors interact to regulate the supply and availability of nutrients to tree seedlings.

MECHANICAL INFLUENCES

The presence of residues is usually a hindrance in seeding or planting an area. The degree of hindrance depends on the nature, amount, and distribution of residues, steepness of slope, desired spacing of trees, and regeneration method to be used. On the other hand, residues protect soil and seedlings in some degree from sheet erosion, raindrop splash, frost, browsing animals, and other actions of common occurrence on bare soil. Some protective features are lost when residues are reduced or removed by treatment. Furthermore, each method of treatment has its particular effect on the seedbed, on soil characteristics, and on any unwanted vegetation.

PHYSICAL OBSTRUCTION

Residues in Place

Residues occupy surface area making it unavailable for seeding or planting. The surface occupied may be a large part of the total after harvest of defective old-growth Douglas-fir stands or a minor part after close utilization of healthy young growth. The timber type, logging method, degree of utilization, and terrain determine the amount of surface residues will cover (fig. 1). How severely they impinge on followup reforestation effort depends on management's stocking objectives. Area occupied by residues becomes most critical when closely spaced, uniformly distributed young stands are desired.

Residues interfere very little with broadcasting of tree seed. Ground control might be hampered slightly if seeding is done by helicopter or fixed-wing aircraft. If broadcast seeding is done afoot, the sower's travel may be

Figure 1.--On a gentle slope, this slash hinders choice and preparation of planting spot more than it hinders crew travel.

slowed and somewhat restricted, and seed distribution might occasionally be impeded by tall piles of slash. Broadcasting gets seeds into areas that are physically not readily accessible to sowers, but substantial numbers may fall' on residue-covered microsites where chances for seedling establishment are not particularly good.

Seed spotting involves the choosing of spots to sow; residues provide protected spots but also reduce the total number available. Ordinarily, seed spotting requires crew travel across an area in reasonably equidistant parallel lines. Seeds are sown in unprepared or prepared spots at regular intervals and lightly covered with soil. Moderate to heavy residues interfere with straight-line travel, cause irregular spot spacing, and hinder spot selection and preparation. Small, loose residues can be moved, however, and spots can be slipped between large chunks or placed within tangled but protective debris. Seed spotting permits the puncturing of compacted duff and litter which prevent broadcasted seeds from reaching favorable microsites. Spot preparation takes more time in slash and debris than on accessible mineral soil, and some slash-covered areas cannot be reached by 'hand or seeding device.

Planting of nursery stock is obstructed more than seeding is by the presence of residues. Besides keeping surface area inaccessible and hindering crew operation, residues restrict planting of adjacent bare ground. Planters need space to stand firmly and room to swing planting tools--substantially more working room than required for seed spotting. Furthermore, since subsurface conditions often prevent planting of a bare spot, the percentage of total area made inaccessible by residues becomes more critical than for seed spotting. Planting of containerized seedlings requires somewhat less open space than required for planting of bare-root stock; it approaches seed spotting flexibility when a dibble is used to create a hole with a single jab.

A Canadian study by Vyse and Muraro (1973) indicates the effects of heavy logging slash on planting effort. Near the south end of Vancouver Island, slash on a clearcut ranged from 160 to 180 tons per acre (360 to 400 metric tons/ha) near high-lead settings to 120 to 160 tons per acre (270 to 360 metric tons/ha) elsewhere. Before broadcast burning, 14 percent of the area was rated plantable with little or no difficulty; after burning, 100 percent of the area was so rated. On the basis of 450 trees per acre (1,112 per ha), slash burning reduced costs of planting bare-root 2-0 Douglas-fir stock by $30 an acre and planting of container stock by $9. Before slash burning, planting of containers was much cheaper than planting of bare-root stock. In evaluating contract planting costs in southwestern Oregon, Teeguarden (1969) also identified plantable area as "by far the most important single factor.. .."

Residues continue to have some obstructing effects after seedling establishment by seeding or planting. As limbs and debris weather and decompose, pieces shift, bending or covering nearby seedlings. Loosened bark on cull logs and stumps falls onto seedlings growing nearby. Roy (1955) suggests that trees should be planted 4 feet (1.2 m) from a 30-inch (76-cm) bark-covered log, increasing the distance with log diameter to 9 feet (2.7 m) from a 70-inch (178-cm) log. On steep slopes particularly, large logs and assorted debris may move downhill for several years as supporting material gives way. Few, if any, data are available to indicate the impact on total stocking, but residue-caused losses can be found on any regenerated area.

Seeded or planted trees established among and near residues may also benefit from physical protection the residues provide. Deer, cattle, and other large animals normally damage readily available seedlings most. Those located among deep trash or bounded by large logs are most likely to grow unhindered. In some instances, tree limbs and tops have been deliberately piled over planted trees or seedlings in spots to protect them from trampling or browsing. On the other hand, residues also provide hiding places for seed and seedling eaters that hamper seedling establishment among and near residue accumulations (Dimock 1974).

Rough estimates of plantable area are often made as part of preplanting surveys. Such data have generally not been itemized to show the amount of surface area made unavailable by residues. Occupied surface area might be correlated with fuel loading estimates determined for burning purposes. However, Vyse and Muraro (1973) judged that fuel loading was not necessarily related to difficulty of planting since branches caused more travel trouble than logs. Fire hazard "resistance to control" ratings might correlate better, since these reflect the relative difficulty of building a fire trail through slash. Neither of these two indirect means is likely to provide as good estimates of unavailable area and of residue-caused planting difficulties as surveys conducted specifically for the purpose.

After Treatment

Few, if any, methods of treatment now in use totally eliminate residues as physical obstacles to regeneration establishment. More surface becomes available and travel through an area is hampered less when treatments partly consume, change the form, redistribute, or remove residues. Lacking specific data, descriptive accounts must suffice to indicate how different residue treatments facilitate reforestation efforts, particularly planting.

Crushing or scattering of residues facilitates travel over an area but may make only limited additional surface available for planting of trees. Crushing buries undetermined quantities of branchwood, chunks, duff, and litter in the surface soil (Dell and Ward 1969). Such buried material physically interferes with planting; its incorporation loosens, aerates, and dries surface soil and leads to temporary nitrogen deficiencies as the available supply is tied up in wood decay processes. Scattering light residues might make nearly all surface area available for planting or seeding; uniform scattering of heavy residues might handicap the tree planter everywhere.

Broadcast burning removes a substantial portion of the slash which restricts and slows planting (fig. 2). On 58 matched pairs of burned and unburned plots located on clearcuts in the Cascade and Coast Ranges, Morris (1970) found that slash fire burned nearly all small residues, but most logs larger than 11 inches (27.9 cm) in diameter remained. Interlaced small logs were generally gone and beds of litter and rotten wood much reduced. In northern California, broadcast burning of patch cuts in young-growth ponderosa pine *(Pinus* ***ponderosa*** Laws.) produced roughly similar results (Hall 1967a, 1967b). Between 70 and 90 percent of fuels less than 4 inches (10.2 cm) in diameter were consumed, but less than 50 percent of those larger than 4 inches. If slash is piled or windrowed before burning, a substantially greater percentage of the total will be consumed. Travel over an area is then virtually unhampered, and most of the surface is accessible for planting or seeding.

Reduction of residues by chipping has been suggested in lieu of fire. Chips serve as mulch to protect the soil surface, but they are certain to obstruct seeding or planting efforts. Chipped slash from an average logging operation in western Washington might cover the soil surface 5 to 8 inches (13 to 20 cm) deep if uniformly spread (Anonymous 1972). Planters would then have to scrape 3 to 5 square feet (0.28 to 0.46 m^2) of surface bare of chips to plant a tree. Mixing of chips with soil around the roots must be avoided since chips are likely to foster excessive aeration, loss of soil moisture, and temporary nitrogen deficiency. A deep layer of wood chips would also bar seed from mineral soil, and germinated seedlings would have difficulty growing to it. If chips and intermingled airspaces were large, seedling roots would desiccate; if chips were small enough to foster sustained high water vapor conditions in adjacent airspaces, roots could grow to mineral soil if seed reserves did not become exhausted first. Should chipping and spreading become an accepted residue treatment, size of chips, thickness of the layer, and surface coverage will be critical for either seeding or planting.

Mechanically removing some or all of the slash obviously increases the area available for planting or seeding and facilitates work of the planting crew. If all large, unutilized material is yarded out (YUM yarding), those obstacles particularly difficult to get over, around, or under on steep slopes are eliminated [1] (Adams 1965, Gardner and Hann 1972). The additional yarding would

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[1] Norman E. Gould. Utilization to reduce pollution. Paper presented at Oregon Logging Conference, Eugene, Oregon, Feb. 22, 1968.

Figure 2.--Broadcast burning removes most small fuels, makes more surface available, and facilitates crew travel.

increase the bare surface available on an area and might cancel the need for broadcast burning the remaining finer slash and litter.

On a trial basis, slash has been buried in pits dug on the site. Substantial area is required; a trench 12 to 14 feet (3.7 to 4.3 m) wide, 4 to 5 feet (1.2 to 1.5 m) deep, and 30 to 60 feet (9.1 to 18.3 m) long was required to bury slash and brush found on individual one-fourth acres (0.1 ha) after clearcutting in northern California (Schimke and Dougherty 1966'). Seven years after slash was buried in a shelterwood at Challenge Experimental Forest in California surface slumping was negligible and natural and planted seedlings were doing well./ Much more information must be obtained about long-term effects on stand establishment and growth, however, before slash burial is seriously considered.

SEED BED EFFECTS

Residue influence starts as harvest ends, after some mineral soil has been exposed and loosened, some compacted, some covered with unwanted woody material, and some left undisturbed. If residues are left in place, their primary effect is to stabilize existing seed bed conditions, i.e., to protect covered soil and resist rapid change. Physical nature of covered seed beds is certain to change rapidly if residues are reduced by treatment. Regeneration establishment and growth can be either improved or impaired by individual changes that take place.

2/ Dale O. Hall, personal communication, February 13, 1973.

Residues in Place

A compacted layer of duff, litter, and associated fungal growth is naturally present under many forest stands in the Pacific Northwest. Whether covered by limbs and tops or present undisturbed after logging, such a layer presents a physical barrier to the establishment of natural or artificial regeneration. Until it separates or decomposes over several years, this is the seed bed for seedling establishment from natural seed fall or broadcast seeding. Such a layer often keeps a seed from reaching a favorable microsite. It may physically impede penetration by the radicle of a germinating seed and to some extent hinder the downward percolation of precipitation. Litter and duff layers dry out quickly, providing inhospitable environments for seed germination and rooting of seedlings. Planters or seed spotters must scrape away duff and litter to get trees or seeds into mineral soil. They must also keep it out of the planting spot to reduce aeration and moisture loss.

When deep piles of slash or thick duff and litter layers cover an area, development of new vegetation is slowed. Indirectly, tree regeneration may be affected too, since in some situations its establishment among residues hinges on the changed environmental conditions such vegetation might produce. Should living brush and forbs be part of the residues present, they often develop quickly to occupy the area, providing both shade and competition affecting tree establishment (Morris 1970).

After Treatment

A good broadcast burn will eliminate most of the undesired duff and litter which interferes with regeneration establishment but may also produce some unfavorable changes. Where the burn is light, only uncompacted litter is consumed, leaving a blackened organic layer still covering the soil surface--particularly at higher elevations where such layers are often deep and moist. Surface of mineral soil bared by burning residues is darkened by charred organic matter. Inevitably, concentrations of slash will burn intensely, producing deep ashes and changes in both color and physical structure of surface soil (Austin and Baisinger 1955; Tarrant 1953, 1956). Studies have shown that such changes affect a minor part of the total area (Morris 1970; Tarrant 1954, 1956) and are usually not considered a serious factor in regeneration establishment. Deep or crusted ashes and baked soil found on severely burned spots resist wetting by light precipitation and form a structureless, gooey mass when thoroughly soaked. This condition does not appear favorable for regeneration establishment, but its effects have not received specific study in the Pacific Northwest.

Evidence from Montana indicates that establishment and growth of regeneration are adversely affected for a long period on such spots (Vogl and Ryder 1969). It seems prudent to minimize the creation of intensely burned soil by spreading out heavy concentrations of residues and not purposely creating big piles to facilitate burning.

Once thoroughly dried, some duff and litter layers resist rewetting, particularly those blackened by slash fire. Such layers may prevent light precipitation from percolating to the root zone and could slow the seasonal recharge of soil moisture. Evidence for the creation of water-repellent layers in the soil as a consequence of slash burning has been reported (DeBano and Rice 1973, DeByle 1973, DeByle and Packer 1970). Such repellency may be near the surface after a light fire or as much as 15 centimeters (5.9 in) deep following a hot fire. The induced repellency appears to be least if slash is burned when the soil is moist. The water repellency of soils has come under systematic study only recently. Little is known about the extent of its occurrence naturally in forested areas, its duration following various treatments, or how much it affects tree establishment by either seeding or planting.

Whenever residues are treated or moved by machinery, some soil compaction is likely to occur. The amount and severity depends on the pressure applied per square inch of ground surface, number of passes over a given spot, soil texture, soil moisture content, and other factors. Generally, machine bunching or transporting of slash is done in the summer when surface soil is driest. Potential for compaction is then substantially less than during logging when soil is likely to be more moist and repeated trips are made over the same skid roads. In fact, if slash is bunched by means of raker teeth attached to the dozer blade, there is substantial likelihood that some compaction produced during logging will be ameliorated. Compaction is modified by natural processes; thus, its effects are greatest at first and lessen with time (Mace 1971, Tackle 1962). The multiple adverse effects of compaction on soil permeability, aeration, water-holding capacity, etc., are discussed by Rothacher and Lopushinsky (1974).

Seedling establishment and growth are influenced by soil compaction. In one study, over twice as many seedlings established naturally on tractor-logged areas as on adjacent skid roads. In relation to unlogged conditions, soil bulk density was 2.4 percent greater in logged areas and 15 percent greater on skid roads (Steinbrenner and Gessel 1955, 1956). Over 41 percent of the seedlings were judged to be of poor quality on skid roads compared with 12 percent on adjacent cutover. On two areas in western Oregon, growth of 2-0 Douglas-fir seedlings planted on skid roads with an initial soil bulk density of 1.5 to 1.7 was substantially less than on adjacent cutover with a bulk density of 0.87 to 0.98 (Youngberg 1959). In a greenhouse study, roots of seven northwestern species penetrated sandy loam soil with a bulk density of 1.32; only red alder (*Alnus mbra* Bong.), Douglas-fir, and lodgepole pine (***Pinus** eontorta* Dougl.) penetrated at 1.45; and no species penetrated at 1.59 (Minore et al. 1969). Sometimes soil compaction may prove beneficial. It has been advocated for improving regeneration establishment from seed on loose pumice soils; Cochran (1973) tried to increase thermal conductivity and thus moderate surface temperatures by compacting surface layers.

As residues are treated or moved, additional mineral soil is exposed to weathering and erosion with attendant benefits and adversities for seeds and seedlings. When residues are burned, the surface layers of mineral soil are not stirred up; most other residue treatments dislodge surface soil and sometimes deeper layers. Generally, subsoil is not as conducive to seedling establishment and growth as topsoil. On the other hand, loosened surface soil and light sheet erosion combine to lodge seed in favorable microsites for ready establishment and growth.

Although erosion moves seed, topsoil, and readily available nutrients and perhaps carries them off the site, the burial of seedlings is probably its primary detrimental effect. Surface materials move down bare slopes steadily under the impetus of gravity, freezing and thawing, and animal activities. In the Oregon Cascades, soil movement, primarily dry ravel, averaged 89.6 cubic feet per acre (6.3 m^3/ha) on 80-percent slopes, 20.6 cubic feet per acre (1.4 m^3/ha) on 60-percent slopes during the first growing season after burning

(Mersereau and Dyrness 1972). Movement on bare, 80-percent slopes was 46 times greater than on vegetated 60-percent slopes.

Downslope movement of material bends or buries seedlings (fig. 3). In one instance, 23 percent of the 2-0 and 8 percent of the 3-0 Douglas-fir seedlings planted on a 50-percent south slope were buried by the end of the first growing season (Berntsen 1958). Obviously, if so many good-size seedlings are buried, many more small seedlings developing from seed will be lost. Locating seedlings on benches or at the front of small terraces created during planting and beside protective but bark-free stumps will minimize losses (Franklin and Rothacher 1962). Some seedlings are also buried by slides and slumps, or seedling roots are laid bare by water-caused erosion, but such losses are likely to be a minor part of the total.

On bare soil, seedlings are also exposed to mud splash caused by raindrops, lifting through frost action, and more wind. A coating of mud interferes with seedling photosynthesis and may be physically damaging. The action of ice crystals lifts small seedlings, particularly on moist clay soils, breaking their roots and sometimes raising them clear out of the ground (Schramm 1958). The smaller the seedling, the more likely that either rain splash or frost heaving will be fatal.

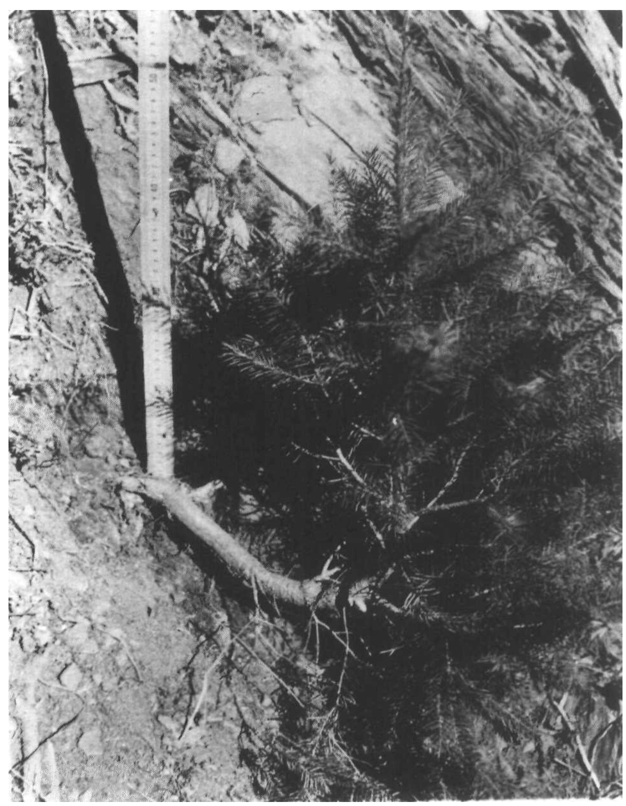

Figure 3.--Downslope movement of soil, rock, and other materials bends seedlings severely, retarding their growth.

In open locations, seedling stems are sometimes seriously abraded by wind-transported particles or stems are rubbed against sharp materials in the adjacent soil.

Sometimes the choice of treating slash or not treating it hinges on a specific season or circumstance. If enough advance regeneration survives logging, it may be prudent to leave slash that might normally be treated (Hall and Neal 1963). Where lodgepole pine bears serotinous cones, it is advantageous to save part of the slash to provide seed for regeneration of the area (Boe 1956, Tackle 1964). In other forest types, residue treatment might logically be cancelled or altered if a crop of seeds has fallen which is likely to restock the area.

ENVIRONMENTAL INFLUENCES

The key environmental factors bearing on seedling establishment and growth-light, temperature, moisture, and nutrients--are affected in various degrees by the presence or removal of residues. As with mechanical influences, some of the resulting environmental effects benefit and others hinder tree seedlings. In a broad sense, the environmental effects must be considered an aftermath of mechanical influence, for it is the physical presence or removal of residues that materially alters the environmental complex at individual microsites. In general, consequent microsite adversities affect tender seedlings produced from seed more than planted trees, but the latter are also affected. Furthermore, some residue-produced conditions favorable for tree establishment are not necessarily best for later growth and development.

RESIDUES IN PLACE

Shade

Shade provided by slash, naturally accumulated litter, stumps, rocks, residual live trees, and brush is the single most important ameliorating influence on the seedling's site-determined environment. Shade-producing residue has multiple effects--primarily reduction of insolation, temperature extremes, moisture loss, and wind movement. Its key moderating influence may be on one environmental factor in one instance, on another factor in different circumstances. The multiple effects of shade have generally not been evaluated by component parts, i.e., benefits ascribable to changes in light, temperature, wind, etc. The amount of shade provided by residues will depend on timber type, nature of initial stand, harvesting method, utilization standards, geographic features, and other factors. Little has been done to quantify the amount of shade provided by different residues.

Direct and circumstantial evidence from many studies indicates that shade provided by residues, live brush, or tree canopies is beneficial for seedling establishment from natural seed fall or direct seedings. Better regeneration success has been reported on shade-protected sites than on exposed sites in many forest types including coastal Douglas-fir (Franklin 1963, Garman 1955, Isaac 1943, McCulloch 1942, Williamson 1973), Rocky Mountain 'Douglas-fir (Hatch and Lotan 1969, Krauch 1956, Ryker and Potter 1970), red fir-white fir (Gordon 1970a), western hemlock-Sitka spruce (Ruth 1968), Engelmann spruce-subalpine fir (Day 1964), and western larch (Shearer 1967). Sitka spruce (***Picea** sitchensis* (Bong.) Carr.) and western hemlock (***Tsuga** heterophylla* (Raf.) Sarg.) seedlings established and grew better in light than in heavy slash and vegetation on a coastal cutover (Berntsen 1955), and better on duff and rotten wood under partial canopy than in the open (Minore 1972). It is noteworthy that shade has proved beneficial even in coastal locations where environmental conditions are not particularly severe. Naturally, the degree of difference in seedling establishment between shaded and exposed microsites varies with aspect, soil surface conditions, and geographic location.

Evidence from several studies demonstrates that on some sites planted trees also benefit from shade. In the central Rocky Mountains, Engelmann spruce survival was substantially greater when planted seedlings were shaded with wooden shingles (Ronco 1970b). An early test in the northern Rocky Mountains showed that in August of their first season, survival of ponderosa pine was higher under brush than in intermediate or open locations (Wahlenberg 1930). In California, very light slash or protection provided by box shook, cotton "batten," or sheet metal aided the survival of ponderosa pine (Maguire 1955, Roy 1953). At high elevations in the true fir type, shade provided by sheet metal enhanced high 3-year survival of 2-0 red fir *(Abies magnifica* A. Murr.) about 20 percent (Gordon 1970b). In southwestern Oregon, second-year survival of 2-0 Douglas-fir was 60, 47, and 10 percent in shade from wood or rocks, brush or trees, or in the open, respectively (Minore 1971). In a coastal California test, 72 percent of spring-planted 1-1 Douglas-fir shaded by shingles survived, only 32 percent of those unshaded; but shaded and unshaded results for 1-0 Douglas-fir were about the same, 34- and 30-percent survival, respectively (Adams et al. 1966). Nor did shade significantly improve the good survival of Douglas-fir planted on steep south slopes in two northwestern California locations (Strothmann 1971, Strothman 1972). Such contradictory results raise doubts about the consistent need for shading planted trees. Nevertheless, planters are generally instructed to plant trees in the shade of cull logs, rocks, stumps, tops, wood chunks, and brush present on the site.

Although shade provided by trees and brush is generally beneficial for establishment of seeded or planted trees, such living cover often severely hinders subsequent seedling growth and development. For example, after extensive planting studies in northern California, Show (1924, 1930) reported that shade from brush aided survival of ponderosa pine and other species and concluded, "On poor sites for all species the need for shade is greater than on good sites." Ponderosa pines shaded most made the best height growth, yet after seven seasons averaged only 1.6 ft (49.7 cm) tall. Many similar experiences on severe sites in California and elsewhere have led to recommendations for thorough site prepdration (Foiles and Curtis 1973, Schubert and Adams 1971). Also in the Coast Ranges of Oregon and Washington, tall overtopping brush severely handicaps plantation development (Ruth 1956). In the Oregon Cascades, height growth of six naturally established species and two that were planted was substantially less under competition from *Ceanothus* brush compared with growth in the open (Zavitkovski et al. 1969). Many factors--including brush species, density, and height; climatic severity of the site; timing of tree and brush establishment; and seedling or planted tree characteristics--determine whether the net result of tree establishment and growth under live shade is favorable or unfavorable.

Information on desirable levels of shade for good seedling survival and growth is available primarily for Douglas-fir. In southern Washington, 44 percent of the seedlings that germinated in seed spots exposed to full sun were alive after three seasons; 68, 8, and 0 percent of those under lath shade allowing about 20, 10, and 3 percent of midday maximum sunlight, respectively, were alive (Isaac 1943). Corresponding survival for planted 2-0 Douglas-firs was 68, 88, 62, and 2 percent, respectively. Third-year survival of 2-0 Douglas-firs planted under light young-growth, heavy young-growth, and virgin old-growth forest (midday maximum light values 5.4, 3.4, and 1.9 percent of full sun) was 62, 9, and 0 percent, respectively. After 9 years, planted trees growing in the open were twice as tall and much stouter than those growing in about 75-percent shade (Isaac 1963). Relationships on a hot, south-facing slope in northwestern California were similar, but data reflect the more severe conditions (Strothman 1972). Germination was highest under lath providing 50-percent shade, next best under 75-percent shade. After two seasons, survival was best under 50-percent shade, next best under 25-percent, and 0 on unshaded spots. Again, planted Douglas-firs grew best in the open; dry weight, stem diameter, root length, and height growth were less for those growing under 25-percent or more shade. When grown in pots under saran cloth at Victoria, B.C., first-season growth of Douglas-fir and western hemlock seedlings was best under 50 to 70 percent of full light (Brix 1970).

In Idaho, first season survival of Rocky Mountain Douglas-fir seedlings in seed spots under 60-percent lath shade was 70 percent; in the open, 32 percent. Early afternoon temperatures at ground level on August 1 averaged 142" F (61° C) in the open, 100° F (38" C) in the shade (Ryker and Potter 1970). In Arizona, ponderosa pine grew best in nearly full sun and satisfactorily in 25-percent shade (Pearson 1950).

Other Effects

Residual hardwood trees and brush that provide shade also produce other effects which help or hinder regeneration. The slowed seedling height growth caused by such cover gives small animals it harbors more seasons to clip seedlings (fig. 4). The annual fall of leaves and litter enriches soil but also forms a layer which can be a partial barrier to penetration by germinating seed and a smothering cover for small seedlings. Certain widespread genera, i.e., *Alnus* and *Ceanothus,* fix atmospheric nitrogen by means of root nodules (Delwiche et al. 1965, Zavitkovski and Newton 1968b). It is not clear that the added nitrogen materially aids seedling establishment and growth, but certainly the site is enriched by such nitrogen fixation (Tarrant 1961; Tarrant and Trappe 1971; Zavitkovski and Newton 1967, 1968a, 1968b).

Residues of all kinds slow air movement, providing primarily beneficial effects for seeded or planted seedlings. They are not subjected as much to cold or hot drying winds, and water vapor is not as rapidly removed from surrounding air and soil. On the other hand, wind movement helps alleviate high temperature buildup near the soil surface during the day or cold air accumulation during the night. Overtopping residues which reduce outgoing longwave radiation help prevent freezing or reduce alternate freezing and thawing that lift and kill seedlings (Cochran 1969a, 1973). In the southern Washington Cascades, frost-caused losses of germinating Douglas-fir seedlings occurred mainly in the open (Isaac 1938).

AFTER TREATMENT

Any residue treatment reduces the shade and other protection afforded to seedlings or planted trees and generally causes greater extremes at the microsite level in one or more environmental factors. Under moderate site and climatic situations in the Pacific Northwest, these changes are not so extreme, universal,

Figure 4.--Clipped repeatedly by rabbits, this overtopped, planted ponderosa pine under **Ceanothus** *brush eventually died.*

or long-lasting as to preclude satisfactory regeneration establishment. But under more severe situations, removal of residues may have substantial and long-lasting adverse effects on regeneration establishment. Only a limited number of studies indicate the kind and magnitude of environmental changes that result from residue treatment and the difference caused in regeneration establishment.

Critical Temperatures

Any residue treatment that reduces or breaks up the area covered by unshaded, compact layers of duff and litter is likely to assist regeneration establishment. It is well known that both high and low surface temperatures are more extreme on organic surfaces than on mineral soil (Cochran 1969b, Geiger 1966, Fowler 1974). These differences in temperature extremes and the variable thermal properties of different seed beds are critically important for seedling survival of many species (Haig 1936, Isaac 1938, Shearer 1967). In laboratory tests, for example, Douglas-fir seedlings exposed for 60 minutes under tungsten lamps died at 138° F (59° C) in peat moss, 148° F (64° C) in yellow mineral soil, and 156° F (69° C) in white sand (Silen 1960). Furthermore, less energy is required to heat organic matter to given temperatures than is required to heat the mineral soil (Silen 1960). Moreover, some field-collected evidence indicates that surface temperatures become higher when litter is 1 inch deep than when it is one-fourth inch deep (Gordon 1970a). Tender seedlings are killed in progressively shorter exposure periods as high temperatures rise above a lethal minimum, which for tissues of several conifer species seems to be about 54" C (129" F) (Baker 1929, Silen 1960). The environment in which they develop appears to influence the seedlings' heat tolerance (Keijzer and Hermann 1966).

Under field conditions, lethal temperatures for young seedlings appear quite variable. Mortality of young Douglas-firs was best correlated with melting of 138" F (59" C) temperature pellets placed very near seedling stems; those that escape early lethal temperatures survive later surface temperatures of 140" F (60" C) or higher (Hermann and Chilcote 1965; Silen 1956, 1960). Limited surveys have shown that high percentages of the seed bed surface on slash-burned clearcuts exceed minimum lethal temperatures by the end of the summer in the Cascade Range of Oregon--69 to 97 percent on south slopes, nearly 50 percent on north slopes in one study (Hallin 1968b, Silen 1960). In evaluating temperature-seedling survival relationships, the surface temperature reached immediately adjacent to the seedling stem, not several inches away, is critically important.

Although surface temperatures on an organic layer become extremely hot, the subsurface soil remains substantially cooler than under a bare mineral surface. For example, maximum midsummer temperatures 2 inches (5 cm) beneath organic layers on a cutover near Corvallis, Oregon, averaged 10" to 20" F (6° to 11° C) lower than in bare mineral soil which heated to as much as 114" F (46" C) and sustained high temperatures longer (Hermann 1963). Under the bare surface, a heating effect severe enough to slow or stop root growth (95" F or 35" C) occurred for periods of several hours on warm days. On northern or high elevation sites, such as the white spruce-subalpine fir type in British Columbia, removal of a litter layer or other residues may be desirable to raise soil temperatures, thus stimulating seed germination and seedling growth (Dobbs and McMinn 1973).

If residues are removed by a light or moderate burn, the seed bed surface is blackened and the likelihood of killing surface temperatures increased. For example, when air temperature during the first hot day on a cutover near Carson, Washington, reached 89" F (32" C) surface temperature on a yellow mineral soil reached 125" F (52" C), and on a blackened surface 143" F (62" C). Within 3 days, all natural Douglas-fir seedlings on the blackened surface died, but only 16 percent of those on the mineral soil (Isaac 1930). When seed spotting or planting, darkened or organic-covered surfaces can be avoided, or removed by scalping chosen spots.

Residue treatments that loosen and roughen the surface soil create some shaded microsites but also induce higher surface temperatures. Loosened soil dries out quickly; as soil moisture content near the surface decreases, the surface temperature increases (Cochran 1969b), again to the detriment of young seedlings.

Soil Moisture

Moisture loss is greater from exposed mineral soils than from those protected by nonliving residues. Heating of the soil and loss of soil moisture are concurrent; moist soils do not heat as much as dry soils. Moisture stresses found under various seed beds on a cutover in the Oregon Coast Ranges illustrate the difference that may develop (Hermann 1963). Soil moisture tension reached 1 atmosphere

2 inches (5 cm) below unburned and hard-burned mineral soil surfaces in early July, below a litter-covered surface in mid-July, and below a charcoal-covered surface a little later. It reached 15 atmospheres below the unburned soil surface shortly after July 15, below hard-burned and litter surfaces about August 1, and below charcoal after August 15. Highest soil moisture tension, about 20 atmospheres, occurred in soil with the surface bare. When severe soil moisture stress is delayed 2 weeks or more, seedlings have a longer period for effective root and top growth which, in turn, fits them to withstand greater stresses. Organic layers that produce surface temperatures which kill newly germinated seedlings might, on the other hand, conserve the soil moisture critical for survival of planted trees.

Although surface temperatures and evaporative moisture losses are less in the shade of live brush and trees than in the open, such moisture savings frequently do not compensate for the moisture used by the vegetation. Despite higher surface temperatures, moisture levels are often greater in exposed soil than in soil under various living canopies. Some examples: In ponderosa pine spacing trials in central Oregon, moisture depletion from pumice soil increased with density of the tree canopy and was 45 percent greater when competing understory vegetation developed normally than when it was kept out (Barrett and Youngberg 1965). Also in central Oregon, soil moisture at 10- to 14-inch (25- to 36-cm) depth under live manzanita brush was 8 percent by September 8, nearly 20 percent under brush killed by aerial spray or where it had been removed mechanically (Tarrant 1957). Spraying chaparral in southern California produced similar moisture savings (Merriam 7961). In southwestern Oregon, soil moisture tensions at 6-inch (15-cm) depth in revegetated cutovers ranged between 18 and 85 atmospheres in the driest part of the summer; where vegetation was removed, tensions only reached 3 to 13 atmospheres (Hallin 1968a). Vegetation developing in 3 years on a clearcut area was about as effective as an adjacent old-growth timber stand in depleting soil moisture (Hallin 1967). When drought is a critical factor, the soil moisture retained by reducing vegetative competition aids seedling survival and growth, as was demonstrated in Idaho ponderosa pine plantations where brush had been removed in strips prior to planting and left intact in adjacent strips (Curtis and Coonrod 1961, Hall and Curtis 1970).

Nurse crops, primarily of India mustard, have been used to shade burned seed bed surfaces, but mustard's use of soil moisture adversely affected seedling establishment (Chilcote 1957). Spraying the mustard saved soil moisture but harmed Douglas-fir seedlings (McKell and Finnis 1957). Sometimes the net effects of using native or exotic plants for shade are beneficial--Youngberg (1966) reported that in central Oregon moisture became critical later under live manzanita or snowbrush than in root-occupied areas between the clumps.

Other Effects

Sometimes photosynthesis of unshaded seedlings is directly impaired by intense solar radiation rather than indirectly through increases in soil surface temperatures and water stress. Such injury has been confirmed for planted Engelmann spruce at high elevations in the Rocky Mountains, but associated lodgepole pine is not harmed (Ronco 1970a, 1973). Direct insolation damage seems likely for several other species growing at high elevations where incoming radiation is not attenuated. It might occur at lower elevations too but has not been studied.

Burning of residues materially affects nutrient status of seed beds; other residue treatments are likely to cause lesser effects. It is generally recognized that slash burning makes nutrients more readily available, drives off nitrogen, reduces organic matter content, and temporarily raises the pH of the soil (Austin and Baisinger 1955; Isaac and Hopkins 1937; Tarrant 1953, 1954). The pH changes may further influence nutrient availability and also increase seedling losses to damping-off diseases (Tarrant 1956). Treatments that transport residues from the site will take some nutrient capital along; those that incorporate woody material into soil--crushing, burying, and perhaps chipping--will foster increased soil organism activity which temporarily ties up nitrogen. The extent and seriousness of these events for seedling or planted tree survival and growth have received little quantitative investigation.

Choice of residue treatment may materially influence species composition of the next stand. For example, on control plots in western larch-Engelmann spruce clearcuttings, subalpine fir *(Abies Zasiocarpa* (Hook.) Nutt.) and mountain hemlock *(Tsuga mertensiana* (Bong.) Carr.) regeneration predominated. Burning or scarification increased the proportion of plots naturally stocked with Douglas-fir, grand fir *(Abies grandis* (Dougl.) Lindl.), Engelmann spruce, or western larch (*Larix occidentalis* Nutt.) (Boyd and Dietschman 1969). Similar results might be expected if mixtures of seeds were sown.

A variety of treatment-connected environmental effects that are clearly or potentially important under different circumstances should be recognized. Removal of residues allows more wind movement which increases transpiration and desiccation of seedlings. Burning or mechanical residue removal eliminates vegetation which provides shade but competes for soil moisture. These same practices can stimulate germination and regrowth of competing vegetation with its attendant beneficial and adverse effects on seedling establishment and growth (Gratkowski 1974). Changes in soil moisture and temperature regimes either benefit or hinder populations of soil oraanisms--the diseases that attack seedlings; the mycorrhizal fungi that aid nutrition and water uptake, and furnish disease protection; and many others. All of those mentioned above and some not touched on are influencing factors, but their quantitative effects on seedling survival and growth have not even been estimated.

DISCUSSION AND RESEARCH RECOMMENDATIONS

STATE OF KNOWLEDGE

The preceding review covering the mechanical and environmental influences of residues on seeding and planting demonstrates the complexity of the subject. All the physical and biological factors that affect the establishment, well-being, and growth of young trees of many species are involved. Except for seed supply, every nature-controlled factor applicable to postharvest natural regeneration also pertains to broadcast seeding. A few less pertain to seed spotting since man exercises some control over placement of the seed and preparation of the spot seeded. Planting of hardened nursery stock represents a further step in bypassing the natural adversities that beset seeds and tender young seedlings. Direct seeding and planting require organized human effort, which also adds a planning, timing, and logistics dimension more demanding than required when relying on natural regeneration.

The information presented represents but a skeleton outline of the knowledge necessary to intensively and scientifically manipulate residues and other environmental components for the prompt establishment of well-stocked young plantations. Though numerous, the references cited and reviewed and the information they contain would appear slim indeed if separated by timber types, habitat types, or other biological units to which each might logically pertain. Furthermore, few really deal quantitatively and in depth with the subject matter reported. For example, one can draw the inescapable conclusion that shade is beneficial. But why is it beneficial in various circumstances? Is it because total insolation is reduced, surface temperatures ameliorated, certain competing vegetation depressed, soil temperatures kept cooler, soil moisture conserved, or what? And how much shade is necessary, optimum, or the maximum tolerable? We cannot realistically assess residue impacts on regeneration when we don't know sufficiently well the environmental combinations in which seedlings become established and attain acceptable growth. We are also forced to talk in vague terms about residues. Quantities for different forest types and stands may be known, but information on the amount of plantable area they cover or shade they cast is not known. And how much does the shade they provide change with time? Lacking such basic information necessary for sizing up the pros and cons of any proposed treatment, how can we begin to assess more subtle interrelationships?

Much more information on residue-regeneration relationships could be assembled cooperatively with a moderate expenditure of effort. Published literature contains mainly the results developed through experimental studies conducted at a few locations. As such, these findings are really very limited samples of events occurring in a much larger universe of residue-regeneration interactions. The result produced on each cutover where residues are treated and reforestation is attempted constitutes one more sample from which to gain knowledge. Slash treatment and reforestation records for thousands of areas are in company and agency files. So too are slash abatement and reforestation inspection records resulting from enforcement of State forest practice acts. Surprisingly, few systematic attempts have been made to summarize the wealth of accumulated biological information these records contain. Such available information needs to be summarized and analyzed to better identify residue-reforestation practices that produced or failed to produce satisfactory restocking in different timber types, regions, and geographic locations. Though there would be shortcomings, information from such administrative records could prove invaluable in identifying successful and unsuccessful practices and critical problem situations or locations.

The conditions needed for ready establishment of direct seeded or planted trees can now be described only in broad generalizations. Basically, moderate temperatures, sufficient light, plenty of moisture and nutrients, reasonable protection, and insignificant vegetative competition are needed, plus unhampered freedom for movement of crews over the area to be regenerated. Residues are useful only to the extent that they favorably influence or protect the seedling environment more readily than possible by other means. Much more quantitative data is needed to translate these generalizations into meaningful, comparative, and practical terms. Better definition of site conditions and seedling requirements should result in more certain attainment of adequate stocking--a sufficient number of fast-growing, well-distributed trees on all areas to be reforested.

FOREST MANAGEMENT TRENDS

Reforestation and residue treatment are both activities which support and facilitate broad forest management goals. Adequacy of the knowledge now available and priorities for future research on these related endeavors must be judged in the light of management goals and current trends. Ever greater and more intensive use is the continuing trend for most forested lands. Shorn of qualifying conditions, the long-term goal is to maximize goods and services which forest lands can produce. Applied to residues, this means maximum protection for existing forest resources and maintenance of future productivity; applied to reforestation, it means minimum delay and maximum flexibility in establishing new crops of trees.

Decisions and events which precede the time for residue disposal and reforestation greatly influence the final outcome. Choice of harvesting method for a particular stand is, consciously or unconsciously, a choice of slash load to be created and environmental conditions to be provided for seedlings. Designation of logging method is another choice bearing on residue-regeneration relationships, and utilization standard still another. Utilization standards are particularly significant; if current trends continue, there will be little large material left on cutover areas to be physically obstructive or to provide shade. .Such major changes, now already taking place, can render obsolete the results of past studies on residue-regeneration relationships.

Trends in harvesting practices and the bases for the choices made are particularly important for giving direction to regeneration research. For several decades, clearcutting in patches and broadcast burning of slash have been standard practice in the coastal Douglas-fir region, and the system has been applied in other types as well. At first, natural regeneration was usually relied on to restock clearcuts; later, broadcast seeding was practiced extensively; and now, planting of bare-root and containerized seedlings predominates. These changes in reforestation method have occurred despite the rather substantial evidence that much of the harvested area in the Douglas-fir region will restock naturally in a reasonable period of time (Franklin 1963, Isaac 1956, Morris 1970, Williamson 1973). Furthermore, the extensive, long-term study by Morris (1970) showed that both slash-burned and unburned areas became medium stocked or better within 16 years. Direct seeding was favored for a time because it was fast, cheap, and flexible, and it overcame the uncertainties of sporadic seed crops. Planting is favored now because it gives still more certain control of tree establishment. Elimination of regeneration delay has become more important than the cost differences between regeneration methods. Despite some recent renewed use of shelterwood systems, it appears that planting will continue to be first choice among reforestation methods in the foreseeable future, particularly since it offers the most direct and positive means for establishing genetically improved stock.

RESEARCH RECOMMENDATIONS

Ideally, enough should be learned about residue-regeneration relationships to provide the forest manager with a scientifically sound array of residue treatment and reforestation options for every important forest type and subtype. This would require learning a lot about residue characteristics and even more about the quantitative seedling response to various environmental combinations. Such an undertaking would be very large even for a single timber type and would have numerous ramifications. Realistically, sufficient resources to fully evaluate a series of options applicable to natural regeneration, seed spotting, and planting are not in sight. Research must concentrate on the most critical subjects and locations.

These locations are not yet adequately identified. That will require a more systematic evaluation of current practices--where are results quite satisfactory and where are serious shortcomings? Some salient regeneration problems exist in every forest type, but which ones are residue related? The most obvious appear to be in the Siskiyou Mountains of southwestern Oregon, on south and west slopes throughout the Oregon Cascades, and in eastern Oregon and Washington. But within this large territory, there are many localities where regeneration problems are not particularly critical. Thus, better identification of priority areas, perhaps identified by habitat type, is necessary.

Within the habitat types requiring priority attention, put primary emphasis on residue and reforestation studies which will improve survival and growth of bare-root and containerized nursery stock. Key elements to be investigated include:

A. Role of residues

1. How much do current and prospective residue levels obstruct placement and planting of bare-root and containerized trees before and after various treatments?

2. Are the ameliorating effects of different residues sufficient to materially aid seedlings? If not, does the method of removal itself produce critical adversities for regeneration establishment?

3. Are there alternatives to residues which better provide the protective conditions seedlings need, e.g., shade from a residual overstory?

B. Needs of nursery stock

1. What are the conditioning processes necessary to best prepare bare-root and container stock for different habitats?

2. What are acceptable and optimum environmental combinations of light, temperature, moisture, and nutrients for ready establishment of the key species?

3. When should shaded seedlings be released to insure best growth and development?

C. Soil management practices

1. How much do various changes in physical structure of soil affect seedling establishment and growth?

2. Which site preparation practices are best for seedling establishment?

3. What increases in soil fertility will speed seedling development?

Integrated, indepth field studies and related laboratory work will be required to find solutions to these priority problems. Not to be overlooked is a new dimension in management of some forests--residue removal, site preparation, underplanting, and later overstory removal in stands partially cut initially.

Primarily physical and biological information is needed most. Quantitative assessment of environmental conditions provided by current and prospective residue levels and the environmental needs of planted trees should receive priority. We must know what conditions prevail and what conditions are really needed before becoming overly involved in new methods of treatment and special machinery that might prove useful. Furthermore, the effects of treatment cannot be evaluated adequately without knowing clearly the environmental conditions we want to create. Substantial attention will need to be given to harvesting methods. The methods and machinery used determine residue levels, how residues are bunched or scattered, and the extent of seed bed preparation. Well-chosen practices can minimize the need for residue treatment and go far in aiding regeneration establishment.

CURRENT RESEARCH

Ecological and physiological research pertinent to reforestation in the Pacific Northwest is being conducted by many organizations and individuals. It's a large field and many people contribute useful information. However, the focus of these efforts is diffuse. There is not a single program with primary emphasis on residue-regeneration relationships. On the other hand, almost everyone involved in planting or seeding studies partially evaluates residue and seed bed effects when interpreting seedling survival and growth results. Within the Pacific Northwest Forest and Range Experiment Station (Portland, Oregon), the entire programs of Research Work Units on Artificial Reforestation Systems in the Pacific Northwest; Brushfield Reclamation, Prevention, and Ecology; and Control of Animal Damage to Western Conifers concern reforestation. Programs of three research units with assignments on forest types contain material amounts of reforestation research and other units lesser amounts. Substantial reforestation research is also underway at Oregon State University, School of Forestry, Corvallis, Oregon; University of Washington, College of Forest Resources, Seattle, Washington; Washington State University, Department of Forestry and Range Management, Pullman, Washington; and the University of British Columbia, Faculty of Forestry, Vancouver, B.C. The Pacific Forest Research Centre of the Canadian Forestry Service, Victoria, B.C.; Weyerhaeuser Company, Forestry Research Center, Centralia, Washington; and Washington State Department of Natural Resources, Olympia, Washington, also have extensive programs. U.S. Forest Service Experiment Stations outside the Pacific Northwest and numerous other colleges and universities within and outside of the region also produce pertinent information.

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MICROCLIMATE

W.B. Fowler

ABSTRACT

Basic physical processes that underlie the development of local microclimates are examined. Opportunities to affect these processes by residue generation and treatment are examined with respect to a simplified energy balance model and by demonstration of effect of residue types on surface heating and cooling. Potential for the aggravation or amelioration ame of critical limiting conditions in the thermal and moisture regimes of regenerating species is emphasized. Change in exposure and surface physical properties by residue treatment is seen as producing important modifications of the energy balance.

Keywords: Microclimate--surface temperature; energy balance--reflectivity, heat transfer, long-wave radiation; mulch.

INTRODUCTION

Microclimate is simply defined as the essentially uniform local climate of a usually small site or habitat. A characteristic microclimate may extend for several or many meters horizontally, dependent on surface uniformity, but is considered to lose its identity quite rapidly in the vertical as the effects of local conditions are reduced. A distinction, therefore, is often made between microclimate and macroclimate, the latter referring to the large-scale climatic features of an area, characterized by measurements taken at weather shelter height.

Even without formal study of the microclimate, many of the physical factors creating different local microclimates are easily recognized. Exposure to the sun for warmth and shade for cooling, surface moistening, and exposure to wind for evaporative cooling are among the cause and effect solutions to problems of personal comfort. Similarly, the forest plant and its environment heat and cool in response to the exposure to or exclusion of solar radiation, windflow, and use of moisture in evaporation or transpiration.

Understanding these several major physical processes that create differences in local microclimate and how generation and treatment of forest residue can modify them is of immediate interest. As important perhaps is how the physical elements of the microclimate can modify subsequent biological events or activities. Problems most frequently attributed to residue and residue treatment are often biological in nature; e.g., regeneration and survival of acceptable species and rapid natural destruction of residue. The local microclimate factors--radiation, temperature, wind, and moisture--are also recognized as inputs to the large-scale physical process of the area--the hydrologic cycle; they influence water yield, streamflow regulation, and water temperature. In forest management, however, rapid and successful regeneration by seeding or planting is often the principal economic and esthetic necessity. Emphasis in this section is therefore directed toward indicating how the microclimate, especially if influenced by residues, may develop or affect critical limiting conditions encountered in forest establishment. Other biological phenomena or physical processes which may be affected by residue are presumed to be less sensitive to microclimate modification. For example, the residue destruction processes, although influenced by temperature extremes and moisture availability, will remain viable after short periods of inactivity. Similarly, the hydrologic cycle may be altered through residue generation and treatment, but the cycle never ceases.

Repeated failure of natural or artificial regeneration in an area once occupied by a particular species suggests some presently limiting conditions imposed by the environment compared with conditions at inception of the previous stand. An adequate seed source with minimum predation by animals, fungi, and bacteria (Gómez-Pompa et al. 1972) is assumed in these areas. The microclimate may have been inadvertently modified beyond the tolerance of forest seedlings to endure extremes of temperature or drought, possibly by cutting area layout, or possibly by residue treatment.

Although analysis of the delicate balance of inputs acting upon each forest plant is beyond our ability, extremes at the limits of range of climatic variables frequently appear to be especially hazardous to desirable species. Limiting conditions can be imposed through any environmental variable, but most commonly considered are local thermal and moisture conditions--untimely heat and cold and excess or deficient moisture. Timeliness is very important for, although a plant may be able to endure extreme cold--as low as -70° F (-57° C) during dormancy--during active growth, temperatures of +25° to +30° F (-4° to -1° C) may be fatal (Fowells 1965).

The agriculturist has long recognized that certain treatments, e.g., shading, application of mulches, and tillage, can ameliorate particular microclimatic conditions (Abbe 1905). The question is whether stand removal and residue generation and treatment are capable of creating, aggravating, or ameliorating similar limiting conditions within the forest.

Unfortunately, description of the forest environment within this region of diverse climate, the Pacific Northwest, is limited. Basic agro-meteorological statistics, essential to proper management, must be developed from measurements at urban, lowland locations generally atypical of the forest environment.

Also, recognition of events leading to regeneration failures is principally after the fact. Timely examination of these failures may identify a causative agent; often, no simple explanation is apparent. Presumably, many have been closely related to microclimatic conditions.

Literature directly related to effects of residue on the microclimate is quite limited. Some original data have been incorporated to illustrate effects of local reflectivity differences and changes in maximum and minimum temperatures generated by changing thermal and optical properties of surfaces. As one might expect, changes of this nature are quite common with stand treatment.

PHYSICAL CLIMATE

Several physical laws govern the creation of the microclimate at any site. Although the laws and their interrelationships are complex mathematically, a symbolic overview of how they relate can be seen in figure 1.

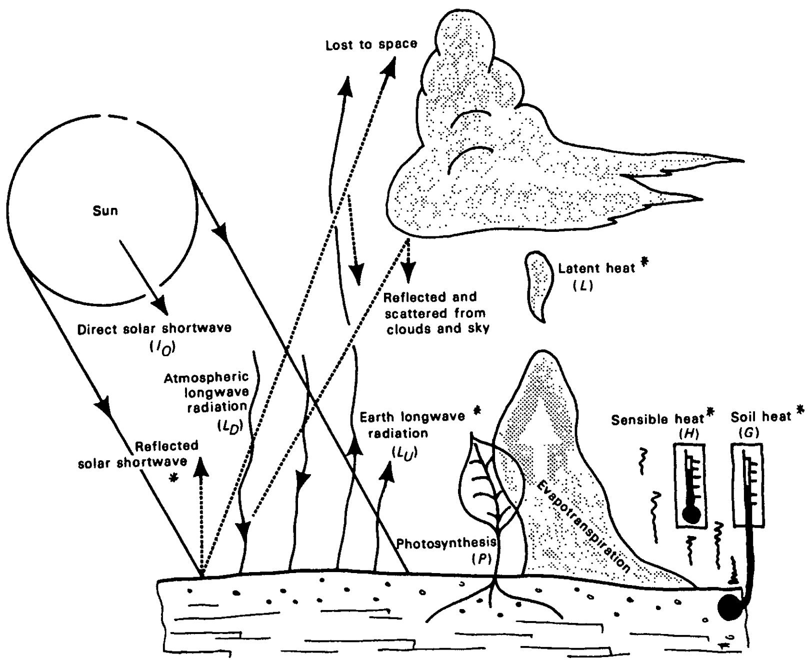

Figure 1.--Typical schematic presentation of the energy balance at the earth's surface. Factors marked with an asterisk (*) are particularly influenced by forest residues and their treatments.

Direct radiation from the sun I_O is not particularly effective in heating the atmosphere as it passes through it. The earth's surface, which can absorb the solar, shortwave radiation is the site of transformation to longwave, heat radiation. This longwave radiation is constantly exchanged between the surface and the atmosphere (shown in fig. 1 as Earth Longwave Radiation, L_U, and Atmospheric Longwave Radiation, L_D). Heat flow through the surface into the soil (Soil Heat, G), into the air by conduction and convection (Sensible Heat, H), used in evapotranspiration (Latent Heat, L), or stored through Photosynthesis (P) provides for the disposition of energy available from the imbalance of solar and longwave exchange. Other small additions or losses of energy to the system or emphasis on special cases are not considered here. A number of excellent publications on this subject are available (Bainbridge et al. 1966, Gates 1966, Gates et al. 1965, Geiger 1965, Reifsnyder and Lull 1965, Sellers 1965, Vézina and Boulter 1966, van Wijk 1963).

At any site, residue can cause some important modifications of the energy balance of the surface. For our purposes some restriction in coverage is possible. For example, direct solar input, I_O (as a function of slope, aspect, latitude, and season), to a surface, the forest canopy, over a silvicultural rotation period may be considered constant. Procedures to calculate this input are available (Lee 1964, Geiger 1965). Atmospheric depletion of the direct solar beam through reflection, absorption, and scattering by clouds, dust, and gases will occur at random and seasonally. These, however, are features of the macroclimate of the area, not directly under local control. The manipulation of the stand by harvest, and the generation and treatment of residue affect principally the receipt of solar energy from canopy surface downward.

Of particular importance in analysis of the energy balance is the reflectivity of the surface material to I_O, the direct solar shortwave. This characteristic, reflectivity (also called albedo), is responsible for the return flow of a portion of both the direct and diffuse solar input. Reflectivity varies from almost total absorption of the incident radiation ($r < .1$ percent) to complete reflection ($r = 100$ percent).

Although the surface treatment of a forest canopy to increase or decrease its reflectivity is technically possible, changes in reflectivity are more probable at the ground surface. We can expect some residues and residue treatments to cause major changes here.

Table 1 shows reflectivity measurements of some potential residue materials taken on June 1, 1972, near solar noon. Most material was measured both dry and wet. Additional tables of reflectivities for a variety of surface materials are available (List 1966, Scholte Ubing 1959). Above-canopy reflectivity for most forest stands and agricultural crops is low, from about 5 to 30 percent depending on species, age, and condition.

Availability of solar energy at the soil surface obviously depends on the overstory. The receipt of sunlight at the forest floor compared with percentage of the canopy closure is not, however, a simple linear function. The canopy is three dimensional--multiple reflections within the canopy space deplete available energy more effectively at low closure percentages than at high percentages. The analysis by Miller (1959) shows a 10 percent closure from 20 to **30** percent causes about a 15-percent change in transmission compared with less than 5-percent change at 60- to 70-percent closure.

The most familiar aspect of canopy shading is the response of plants to the physiologically active part of solar energy available beneath the crown. Species are classified as light or shade responsive or neutral. This concept is adequately elaborated in. most silvics and silviculture texts and not considered further here. The canopy also changes the quality of light at the forest floor. The reflective and absorptive properties of the canopy vary throughout the visible and infrared regions of the spectrum as a complex function of species, density, and season (Gates et al. 1965). Under a canopy, "green" shade contrasts strongly with the neutral attenuation of a dead canopy. Effects of "light" quality on field development of forest species are generally unknown.

The longwave exchange of energy between the earth's surface and the atmosphere (L_U and L_D in figure 1), depends both in magnitude and direction on their relative temperature difference. Any residue treatment that affects the surface temperature at a site modifies the longwave exchange. This exchange is particularly important in the development of 'local radiative frosts. The mechanism involved is considered in more detail below.

Soil heat (G) and sensible heat (H) redistribute energy available at the surface while latent heat (L) requires energy for evaporation and a moisture source. These mechanisms operate along a gradient from hot to cold or moist to dry. Imposition of a barrier to moisture or energy flow, residue acting as a mulch for example, influences the heat or moisture transport.

Table 1.--*Reflectivities1/ of representative surface materials*

Material	Reflectivity	
	Dry	Wet
	----- *Percent* -----	
Needles (pine)	6	--
Needles (spruce)	11	--
Pumice	35	19
Chips (fresh, pine)	36	36
Ash (volcanic)	29	8
Soil	9	4
Bark (fresh, pine)	19	17
Bark (old, pine)	27	18
Sand	21	9
Wood (pine, new)	62	--
Wood (old)	26	1/50
Grass (fresh)	20	19
Grass (old)	24	20
Charcoal (lump)	2	--

1/ Percentage of incident radiation not absorbed by the surface.

2/ Specular (mirrorlike) reflection due to surface water film.

There are opportunities for residue generation and treatment to affect the components of the energy balance and to change the temperature or moisture content of air or soil. Options to explore are (1) shading and exposing, (2) modifying reflectivity of the surface, or (3) influencing the gradient processes of heat flow or evaporation by restricting windflow, temperature rise, or moisture availability.

A more subtle modification of the energy balance can result from local differences in beneath-the-surface physical properties—density, thermal conductivity, and specific heat. Although surfaces with equal reflectivity will absorb equally of the solar energy input, surfaces with dissimilar physical properties will not exhibit the same surface temperature. Consequently, soil heat flow and sensible heat transfer to the air will be dissimilar. Also, the longwave radiative loss is highly temperature dependent and will be dissimilar with changing surface temperatures.

With natural and generated residue materials covering a wide range of reflectivities and internal properties, the following example illustrates some of the potential for modifying the local energy balance.

EFFECT OF REFLECTIVITY AND OTHER PHYSICAL PROPERTIES ON HEATING AND COOLING

Table 2 lists 10 materials of quite different properties which might be found at barren sites or at sites with residue accumulations. Surface temperatures of these materials were measured with an infrared (IR) thermometer. Temperatures were also measured at depths within the materials. Both a daytime heating cycle and a nighttime cooling cycle were analyzed; material was covered and temperature stabilized between exposures. Measurements were made in mid-June in a semidesert climate (Wenatchee, Wash.).

Table 2.--*Material examined under heating and cooling regimes*

Material	Density (bulk)	Specific heat1/	Thermal conductivity	Thermal admittance2/
	$g\ cm^{-3}$	$cal\ g^{-1}\ °C^{-1}$	$cal\ cm^{-1}\ sec^{-1}\ °C^{-1} \times 10^{-3}$	$cal\ cm^{-2}\ sec^{-\frac{1}{2}}\ °C^{-1} \times 10^{-2}$
Pumice	0.35	0.15	0.37	0.44
Wood	.57	.27	.30	.64
Sand	1.60	.20	.4- .7	1.32
Sand and charcoal	1.60	.20	.4- .7	1.32
Bark	.16	(.4)	.15	.31
Needles	.06	(.4)	.08	.13
Soil	1.03	(.2)	.6	1.11
Concrete	2.16	.21	2 -3.5	3.53
Chips	.18	.27	.14	.26
Charcoal	.14	(.2)	.12	.18
Comparative values for other common materials:				
Water	1.00	1.00	1.3 -1.5	3.61
Air	.0012	.24	.05- .06	.01
Ice	.92	.50	5 -7	5.25
Snow	.10	.50	.18	.30

1/ Numbers in parentheses indicate estimated values.

2/ A measure of the sensitivity of materials to temperature change. Equal to the square root of the product of density, specific heat, and thermal conductivity.

Figure 2 is a recording of the surface temperatures during the heating cycle. Two distinct patterns are seen. First, large surface temperature differences developed between the several materials. The highly absorbent charcoal, as we might expect, was warmest and had a surface temperature of about 30" C (54" F) greater than the similarly exposed concrete surface, used to approximate solid rock. Second, surfaces which appeared quite uniform to the eye showed large point-to-point variability--charcoal, chips, and bark, for example, were of this type.

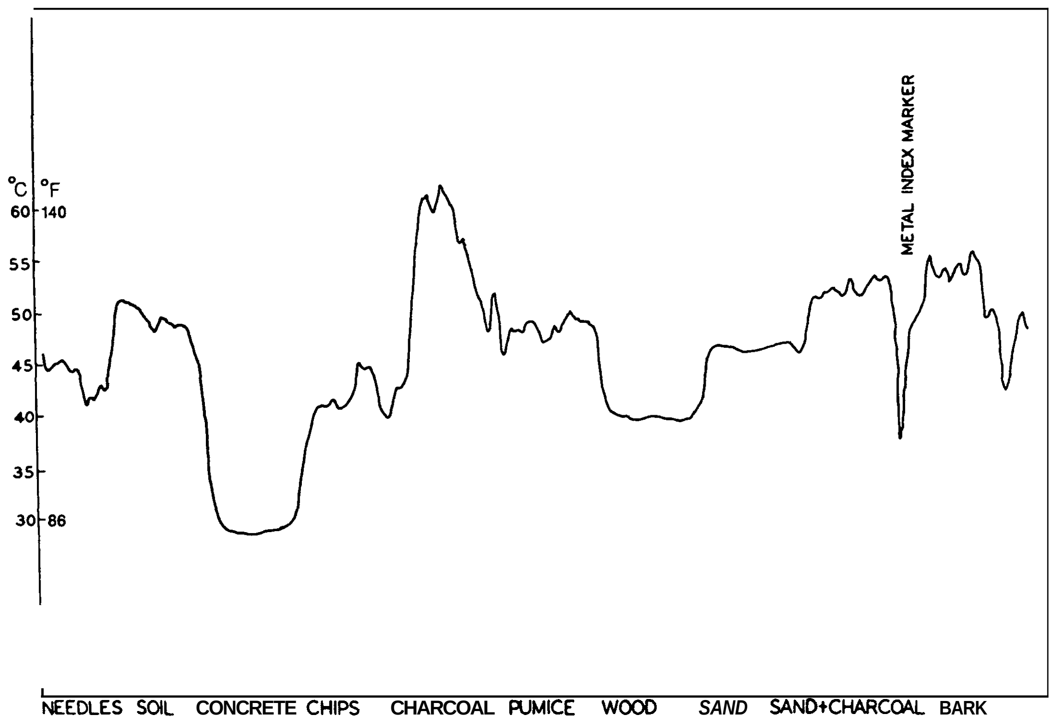

Figure 2.--Surface temperature across beds of various materials exposed to solar radiation.

Figure 3 is the recording of the surface temperatures under the cooling cycle. Compared with figure 2, the range of temperatures between materials is considerably lower, less surface variability occurs within a particular material, and, most obviously, the concrete shows the, highest surface temperature. The temperature difference between the two traces shows the differential cooling rates between the materials.

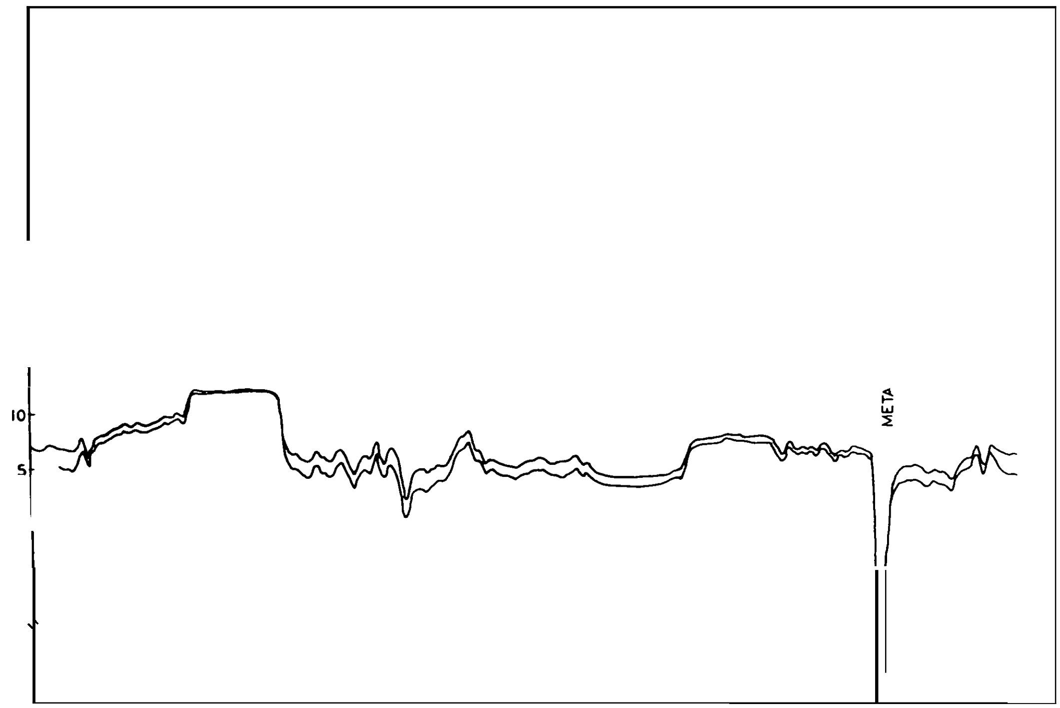

Figure 3.--Surface temperature across beds of various materials exposed to nocturnal cooling.

Details of the internal temperatures are not included here. Materials with the greater difference between nighttime and daytime temperatures, however, showed the greater change in temperature with depth; i.e., steeper temperature gradients.

In the daytime case, the reflectivity of the surface to the solar input I_0 had a major influence on the surface temperature. The question may occur as to why all surfaces with the same or nearly the same reflectivity did not have the same surface temperatures. Or, how can a material with higher reflectivity (not absorbing as much solar input) exhibit a higher surface temperature, e.g., bark compared with charcoal-covered sand?

The answer lies in the physical characteristics of the material, particularly its density (ρ), thermal conductivity (λ), and specific heat (c). In describing the response of a surface to heat flow, it is difficult to separate the role of each of these characteristics. A composite descriptor, thermal admittance, containing these three characteristics as the square root of their product, $(\lambda \rho c)^{\frac{1}{2}}$ is helpful here. Thermal admittance is especially indicative of the ability of energy input to raise the temperature of a surface. Under conditions of equal energy input, a linear relationship between surface temperature and thermal admittance is expected.

To test this concept, data from figures 2 and 3 were compared with calculated thermal admittance, table 2. The nocturnal minimum temperature plot in figure 4 shows surface temperatures follow the expected linear trend. The maximum temperature plot also indicates a trend but is not as well organized. The energy balance at this time is much more complex than in the cooling cycle. The presumption of equal soil heat (G) is not true at this time. This example, however, emphasizes the fact that basic soil properties, surface covering (residue and litter), and reflectivity are important items in the thermal regime of an area.

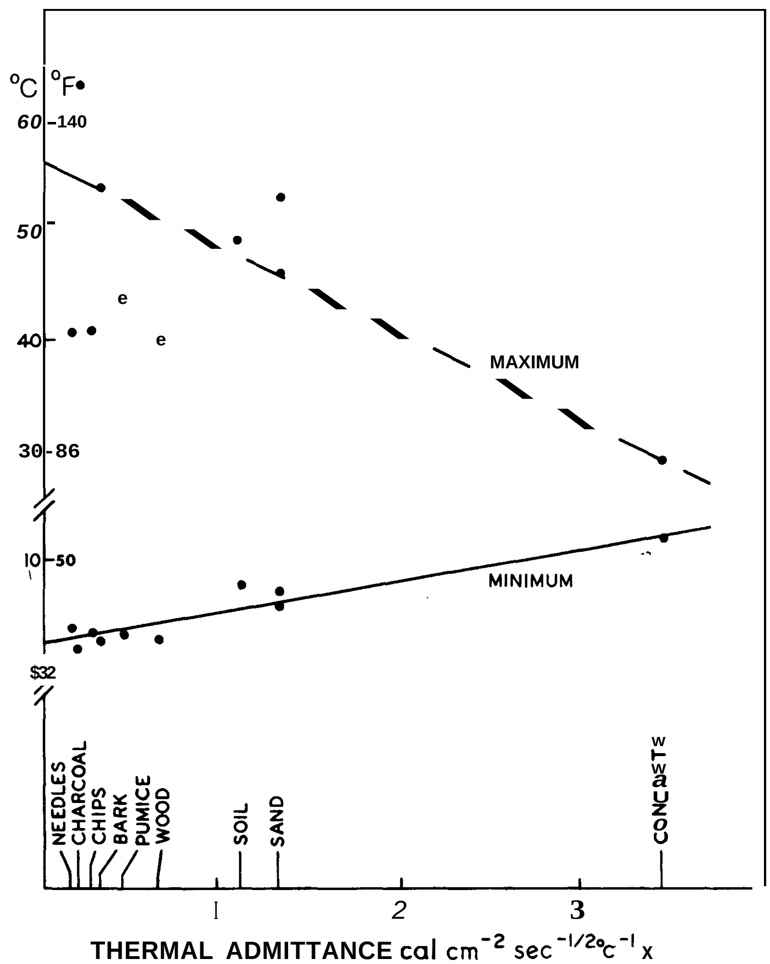

Figure 4.--Relationship between thermal admittance and surface temperature during exposure to solar heating and nocturnal cooling.

The effect of increasing moisture content on surface temperature range was not examined. Floisture can easily be show to have an important role in site response to both heating and cooling of the surface. Values of primary physical constants for air, water, and ice were included in table **2.** Compared with most common materials, water has the highest specific heat and, compared with the air it displaces in bulk materials, about a 1,000-times greater density and 500 times the thermal conductivity. Onsite temperature response with materials under the moisture conditions in the field would therefore be less extreme as moisture contents increase. Cochran (1969b) calculates that surface temperature of a soil with variation between 35" and 125° F (+2° and +52° C) at 35 percent moisture content would range between 13° and 148° F (-10° and 64" C) at 10-percent moisture content. The effect of moisture on reflectivity of these materials (normally decreasing reflectivity with increasing surface moisture) has already been noted in table 1. Evaporation from moistened materials requires additional energy, *L*. With excessive amounts of moisture at the site, the energy use for heating the air, ***H***, is severely restricted; peaty soils or soils moistened by high water tables exemplify this condition. Sites where excessive early season amounts of water are retained and are high in organic materials may experience retarded early season soil and air warming. Later after drying, they develop an extreme surface temperature diurnal range. Both these effects may be detrimental to plant establishment.

FROST AND LIMITS TO RADIATIVE COOLING

In mid-June and in a semidesert climate, high surface temperatures during midafternoon might well have been anticipated, especially on the blackened charcoal surfaces (fig. 2). That these same surfaces at night were able to cool to nearly 18" F (10° C) below ambient (shelter temperature, 52° F (11.5° C)) after a brief exposure may be more surprising. The conditions for their exposure were selected to optimize factors controlling radiative **loss, i.e.,** clear skies, dry air, very low windspeed, and unobstructed view of the sky (Hess 1959, Laikhtman 1961, Vitkevich 1960). This latter factor, "view," in controlling radiative loss from a surface is responsible for many curious phenomena. Easily observed examples of modified radiative **loss** occur when the limits of **a** deposit of dew or frost denote the surface temperature boundary. Decreased rate of cooling of an auto window influenced by an overhanging roof not directly above but only within the "view" from the cooling surface can often be seen on early fall mornings in an abbreviated frost deposit. View of even a leafless deciduous tree may reduce net **loss** sufficiently to prevent a frost or dew deposit. We have not always been as knowledgeable about the cause and effect of dew, frost, and surface temperature. **A** controversy early in the 1800's concerned the question of whether cooling of a surface preceded the formation of a dew deposit or whether the dew caused the observed temperature depressions. **As** documented by Wells (1838), radiative loss and the subsequent cooling which produces dew or frost on objects was strongly affected by obstructions in view from a point on the surface. Both natural and artificial obstructions were included in his study as well as the effects of cloudiness.

The effect of obstruction on minimum temperature is further investigated by Fleagle (1950). He examines the relationship between the zero net radiation temperature of a point, the temperature of obstructions within view from the point, and the percentage of the hemisphere they occupy. The temperature of zero net – radiation of the surface, is a condition in which receipt of atmospheric back radiation (L_D) equals outgoing radiation from the surface (L_U). **He** finds that under static temperature conditions (1) when obstructions are at air temperature and fully obscuring the view, the zero net radiation temperature is equal to air temperature, and (2) when obstructions are at ground temperature, they essentially are ineffective in modifying zero net radiation temperature regardless of coverage.

Cochran (1969a) examines obstruction of view by the boundary vegetation on circular and strip clearcuts in controlling minimum (near surface) temperatures within the clearcut boundaries. In eastern Oregon on pumice soil with a typical high diurnal temperature range, sufficient protection from radiative frosts can be gained through control of stand opening to assure satisfactory lodgepole pine regeneration. Natural regeneration in the openings he examined became scarce beyond a distance equal to boundary tree heights.

Rules of this nature are not necessarily transferrable to other regenerating species or to other macroclimatic zones. Critical temperature limits at periods of the life cycle of the several important forest species will differ. Also, site location, especially elevation, relief, and typical airmass moisture will require local determination. Inland locations under normally dry airmasses will receive less atmospheric back radiation (L_D) than under a moist maritime airmass at a similar air temperature because L_D is strongly governed by atmospheric moisture content. Similarly, low elevation locations compared with high elevations are favorable because of depth of the reradiating atmosphere. Anticipation of state of the atmosphere, especially cloudiness at a critical period, could be particularly important. Areas in deeply incised topography with sites on ridgetops and sidehills will "see" quite different segments of the atmosphere and the surrounding terrestrial features. Relatively smaller openings would be suggested for ridgetop sites on this basis alone. Thus, view obstruction by residue becomes most important at high elevations in dry climates, in large flat openings. Also, creating, aggravating, or ameliorating areas of potential limiting conditions due to radiative frost is strongly determined by the production and removal of overstory.

As a complexity to the simple case of radiative exchange producing locally severe minimum temperatures, density differences within the air cooled at the surface create a flow of cooler air toward lower areas within the site. If the physical depressions are so shallow that the sides do not provide obstruction to radiative exchange, the temperature regime will be even more severe in these depressions. Regrowth of nearby vegetation will eventually ameliorate these harsh sites. Appropriately placed residue accumulation across slopes or near depressions represents a potential solution to these local problems (Geiger 1965, Wang 1967). The depth of the airmass contributing to this cold air drainage may be only centimeters thick but can accumulate to substantial depths at physical obstructions or in hollows.

OTHER PHYSICAL FACTORS

Locally increased moisture supply is an expected complement to any crop removal procedure. This increased moisture supply may be only temporary until the site is again occupied. During this often short period of enhanced moisture supply, timeliness of seed availability or planting is important, especially if the site is marginal in normal moisture supply.

In addition to locally increased moisture supply due to transpiration reduction, use of unmerchantable plant residue as a mulch cover further reduces soil moisture loss.

With the macroclimate of the Pacific Northwest exhibiting generally droughty summers, many sites would undoubtedly be improved with increased summer moisture supply. In addition, agricultural experience indicates that mulches stabilize internal soil temperatures, retain snow, and are valuable in reducing soil erosion and compaction by controlling drop impact and overland flow. Generally, these would be advantages within the forest community but, as Wang (1967) cautions, "mulching alters the physical and chemical properties of at least the topsoil and sometimes the subsoil. Its influences depend on the physical environment of the area concerned, the type of material used, and the method of application."

From the example above of heating and cooling at the surface of beds of materials--several of which would be typical of mulches from forest harvests--some of the disadvantages of forest residues as mulch are seen. Most mulches envisioned here are of lower density material, and less conductive than soils generally. Increased diurnal surface temperature range for these mulch types (bark, chips, needles) would be disadvantageous in most instances. Rates of application necessary to dispose of quantity of unusable material, i.e., depth and type of mulch, must also be considered. Excessive mulch thickness could depress internal soil temperatures beneath levels suitable for root growth and moisture and nutrient uptake. Gas exchange, necessary for root respiration, may also suffer with excessive residue depths. Obviously, rooting habits of newly emerged seedlings would modify rules for mulch applications. Aggressive seedlings--ponderosa pine compared with lodgepole pine, for example--could tolerate deeper mulch conditions. Lodgepole pine, not competitive with ponderosa pine on harsh, dry sites, would benefit from enhanced moisture availability due to mulching at some reduced intensity.

Khil'mi (1957) developed a model to describe the effect of thickness of forest litter on self-seeding of pine and spruce in Russian forests. His analysis indicates a negative exponential relationship between seedling survival and depth of litter.

In his equation $V = V_o e^{-KH}$, V is number of seedlings per unit area, V_o and K are constants and H is depth of litter. Values for V_o and K are species and site dependent. Higher values of K indicate increasing depletion of roots with increasing litter thickness. K for spruce, in Khil'mi's example, was about one-half that of pine and led to the conclusion that "not only the higher shade resistance of spruce, but also the higher capacity of its sprouts to overcome the resistance of the forest litter give it greater advantage in its competition with pine."[1/] Extension of Khil'mi's model to other species and sites was not possible due to lack of data.

Mulching with highly reflective materials is potentially hazardous to seedlings due to increased heat load imposed by the sunlight reflected from the surface (Richards 1970).

1/ Translation would indicate "sprouts" are equivalent to seedlings.

The advantage and disadvantage of mulching and the effect on surface and air temperature at a specific site have, as van Wijk (1963) and others note, been the subject of numerous contradictory statements. Only when the nature of the total energy balance of the site is assessed can the measurements be placed in proper perspective. From even our brief analysis of the processes of soil heating and cooling, sources of several of the potential contradictions can be seen; i.e., (1) reflectivity can be subordinate to other physical properties, (2) moisture content changes thermal properties dramatically, and (3) evaporation can damp out both the soil heating, *G*, and the sensible heat flow to the air, H. Also, single level measurements are particularly unrevealing in potential effect at any site.

Retention of snow cover by brush or strategically located residue accumulations may be a significant hydrologic phenomenon. The potential of increased snow deposits preventing exposure and dessication could be a valuable secondary benefit. A general conclusion is that usually snow accumulation (water equivalent) is greater in openings than in stands due to the interception phenomenon of the stands. Of more importance here is whether snow is retained longer in openings. The Summary Report of the Snow Investigations (U.S. Army Corps of Engineers 1956) concludes that snowmelt may or may not be greater in openings than under trees; however, the last snow to be observed at a site is usually in small clearings. This may be due to increased deposition at these locations. Openings greater in diameter than height of trees have more rapid **loss** of snow cover generally, another factor suggesting control of size of clearings can avoid unseasonable early exposure. Thorud and Duncan (1972) examine the benefit of even a shallow (less than 3 inches (8 cm)) snowpack on depth of soil freezing. Not only were depths of frozen soil less under a snowpack, but the individual differences between surface treatments (litter removal, soil compaction) were minimized beneath the snow cover. Snowless plots also were slower to thaw than snow-covered areas.

Freezing of liquid water within the melting snowpack creates gas diffusion barriers, causes physical damage to plants, or allows deep penetration of excessively cold temperatures due to improved conductivity of the solid ice. All are potentially hazardous to seedlings encased within the snowpack. During fall and spring, frost heaving[2/] in saturated soils may uproot many shallow-rooted plants; amelioration of this latter condition with an appropriate residue treatment, i.e., mulching, may be of some benefit. Plants become less susceptible to frost heaving as stronger roots develop and as crowns provide greater mutual protection against rapid soil temperature change.

Little has been said of latent heat (*L*) or sensible heat transfer (*H*) from the surface, and the influence of residue generation and treatments on these processes. These processes respond to the gradient of heat or moisture and are strongly dependent on turbulent exchange generated by wind and by the roughness of the surface. Generally, higher windspeeds and rapid change of temperature or moisture with height create increased transfer of moisture or heat from the surface.

[2/] Two associated phenomena are noted here--mush frost developing vertically oriented crystal structure, and ice lenses which are more likely of a platelike structure, both of which lift the overlying soil layers.

The effect of windflow and vapor pressure gradient on evaporation has long been recognized. From Dalton's 1802 analysis (Chow 1964), various equations for evaporation based on these two factors have appeared. Evaporation is shown to increase with increase in windflow or vapor pressure gradient or both. Lull (1964) examined the role f wind on transpiration from plants on the Coshocton, Ohio, weighing lysimeter.[3] Compared with still air transpiration rates, at 5 mi/h (2.2 m/sec), there was a 20-percent increase; at 10 mi/h (4.5 m/sec), a 35-percent increase, and at 15 mi/h (6.8 m/sec), a 50-percent increase. Similar increases in transpiration with increasing windspeeds under a variety of conditions have been demonstrated.

Bull and Reynolds (1968) examined wind structure above pine plantations compared with shorter vegetation types. Higher vegetation was found to be aerodynamically rougher and windflow noticeably more turbulent. Residue treatments which create the more aerodynamically roughened surface by piling or windrowing generate turbulence compared with a smoother surface. "The more aerodynamically rough the surface, the more turbulent the airflow and the faster are all the transfer processes.. .vertical profiles of temperature, (air) composition, and horizontal velocity become more uniform with this stirring and mixing process."

Some compensations to the generated turbulence in the transfer process are provided by the impediment of residue to free flow of moisture from the soil column. Similarly, there is the limiting case where obstacles in the airflow become, to a degree, impenetrable and cause the main airflow to separate from the ground surface. Some protection of the area immediately to the lee of these windbreaks, often with reduced evapotranspiration as an added benefit, is noted for distances of 10 or more times obstacle height. This effect decreases with decreasing windspeed. Wang (1967) also noted that, at the limit of the protected zone, turbulence generated by the windbreak may damage plants in this area. Windbreaks may be of living or dead material. Use of forest residues as windbreaks may be appropriate to large expanses of open ground. Effectiveness decreases rapidly in areas already in the lee of a residual stand. Proper orientation of a windbreak to the windflow is important. Orientation parallel to the wind may present a liability for site protection.

As depth of material, e.g., brush, large slash accumulations, etc., increase, air exchange within the zone near the soil surface becomes restricted due to reduction of turbulence and vertical exchange. A minimum air exchange is necessary for removal of toxic gaseous products created by the growing plant and provision of CO_2 and O_2 necessary for photosynthesis and respiration. Huber (1958) indicates the main part of the CO_2 necessary for photosynthesis in field crops is drawn from about 300 ft (100 m) of the atmosphere. Isolation of a single critical factor leading to death of plants under severe accumulations is not possible. Limited vertical air exchange, coupled with inadequate soil aeration (a critical factor for most plants), lowered root temperatures, high soil water retention, and light-limited photosynthesis add to any physical damage. Plants can be effectively "buried" with excessive accumulations.

Influences of residue on the microclimate are found in the specific areas of site regeneration, hydrology, residue destruction, etc. That these many

3/ A device capable of containing a large soil block to measure moisture gains and losses.

processes can be shown to be somehow interrelated is not surprising. Temperature regimes, moisture availability, and energy inflow, outflow, and use are common and essential to both biological and physical processes.

SUMMARY AND CONCLUSIONS

Crop removal, residue generation, and treatment can produce a number of physical effects which may be beneficial or detrimental to overall site quality. In examining site response through the energy balance, certain physical elements were singled out as most likely to aggravate or ameliorate microclimatic conditions. The major effects are summarized:

Effects due to	Energy balance consideration	Management options
1. Exposure	Shading to solar shortwave mutually or by overstory. Longwave, earth and atmosphere exchange (hemispheric view). Radiative frosts.	Intensity of cutting, size and structure of openings, height and density of boundary vegetation, orientation, and spacing. Discouragement and encouragement of nurse crops, brush, planting. Orientation of residue accumulations, artificial barriers. Snow accumulation and retention.
2. Surface characteristics	Reflectivity to solar shortwave input. Temperature of surface in earth-atmosphere exchange. Dependency of surface temperature on soil physical properties. Insulating effect on soil heating, internal energy flow, and modified transfer process. Effect of water on physical properties. Thermal properties of snow versus ice.	Change in reflectivity through deep tillage, residue accumulation, litter and residue treatment (chipping, burning, inclusion). Snow management through residue manipulation for surface covering and shelter. Changing surface bulk properties through tillage or compaction, residue accumulation or removal. Mulch for snow or water retention, evaporation suppression. Water spreading, drainage.
3. Atmospheric transfer	Wind + surface roughness = turbulence; turbulence + property availability = transfer of heat and moisture. Energy requirement in state change (solid, liquid, gas) and stomatal control. Reduction in horizontal gradients with increased flow.	Most options under 1 and 2 affect energy use, availability of properties to be transferred (heat and moisture), and modify the wind structure.

Though adequate site protection and prompt establishment of regeneration, natural or planted, occur in most locations, the potential for changing microclimate through modified residue treatment practices is more important at higher elevations or marginal sites. Some of the basic principles that control these changes in local microclimates were examined and can lead to general summary statements, as above.

Areas about which we need more information include:

1. Species and site interactions: What are the microclimatic requirements at different phases of plant development, and how does the site meet or fail to meet requirements?

2. Site description: Examination of the important zone below standard weather shelter height is necessary, at least at a number of sites representative of the important high elevation forest zones. The importance of probability of occurrence and duration of specific weather factors or events should be emphasized. Lengths of frost-free season, type of frost likely (radiative versus advective), drought, winter protection, i.e., snow cover.

3. Cultural modification: How can the basic energy balance of the site be modified and to what degree? This requires critical onsite examinations of a number of the management options summarized above.

The interrelationship between the microclimate and other physical and biological sciences was noted earlier. Research to clarify or formulate laws relating to the basic atmospheric process, e.g., evapotranspiration, is conducted at most major educational institutions here and abroad. At another level of interest, elements of the microclimate cannot be separated from most studies in the biological sciences, e.g., heat budget of a leaf, temperature effect on soil flora or fauna. This complexity precludes any simple listing of research underway in this broad field. As specifically related to microclimate and residue, some studies of a practical nature are underway, or will soon be, principally as related to silvicultural problems on harsh sites.

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ANIMAL POPULATIONS AND DAMAGE

Edward J. Dimock II

ABSTRACT

Living and nonliving residues remaining after timber harvest exert both favorable and unfavorable influences on forest animal populations. Residue situations usually improve habitats for animals likely to damage regenerating forest crops. Evidence suggests that most residue treatments further enhance the habitats already improved for problem animals by timber harvesting and increase the probability of serious animal damage.

*Practical treatments that modify residues least appear most **promising** for attaining timber, range, and wildlife production goals with a minimum of interference by damaging animals.*

Keywords: Animal damage--forest regeneration, mammals, birds, animal habitat.

INTRODUCTION

Damage to forest crops from a variety of mammals and birds[1/] has concerned mankind ever since the forest was recognized as a renewable source of useful products. The level of concern varies with intensity of management and generally increases in proportion to the likelihood that damage will reduce the net yield of wood. Dollar losses due to animal damage, as inferred from a regionwide survey, run to millions annually (Black et al. 1969). Therefore, this paper will focus upon vertebrates inhabiting forests of the Northwestern States, emphasizing those that cause damage to timber species of chief commercial importance in Oregon and Washington. Most widely recognized forest-animal problems deal with

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1/ Scientific names for trees (Little 1953), lesser plants (Abrams 1940, 1944, 1951; Abrams and Ferris 1960), mammals (Ingles 1965), and birds (Robbins et al. 1966) are listed under "Checklist of Plants and Animals" at the end of this paper.

Douglas-fir and ponderosa pine[2] and occur principally in the *Tsuga heterophylla*, ***Pinus ponderosa***, and *Picea* ***sitchensis*** Zones as described by Franklin and Dyrness (1969). However, a relative dearth of information specific to forests of the Pacific Northwest necessitates much reliance on findings elsewhere for purposes of general inference from parallel situations.

Foraging for food by animals--from the smallest rodent and bird to the largest herbivore--is responsible for most animal damage problems. Depending upon the animal species and the stage of stand development involved, virtually all tree tissues--seed, foliage, bark, roots, and even wood--may be consumed as forage. Since the quantity, quality, and availability of such foods govern the extent to which they will be used by animals, it is not surprising that damage levels generally peak during early stages of stand regeneration and usually decline with advancing stand age (see footnote 2). Crude as this generalization may be, it explains the forester's traditional preoccupation with protecting seed, seedlings, and saplings from damage by animals. Not only is serious loss from mortality and growth retardation most likely during regeneration, but unfavorable consequences may also follow for the bulk of a timber rotation. Moreover, the vulnerable regeneration period most nearly coincides with the time that both living and nonliving residues from preceding stands are apt to be most prominent.

Increases in animal numbers increase the potential for damage to regenerating forests, but only if the expanded populations rely directly on the regenerating tree crop as a food source. The same type and degree of animal foraging might cause serious loss in some cases but inconsequential damage in others. Depredations on tree seed by increased numbers of birds and small mammals, for example, might seriously impair the success of natural or artificial seeding but have no effect on planted seedlings or advance regeneration.

Generally, the greatest changes in density and composition of animal populations result from alterations in forest habitat. Also, the more radical the change the more pronounced and lasting is its effect. Timber harvesting in managed forests is the prime cause of change in the Pacific Northwest, since even the severe and extensive disturbances wrought by windstorm and wildfire are now usually followed by some form of logging. Resulting residues thus suddenly become an integral part of a much altered ecosystem. Though the method of harvesting may vary from clearcutting to some form of partial cutting or salvage, changes in habitat are substantial in most cases.

Timber harvesting creates residues of both living and nonliving material--or, more properly stated, it transforms residues that occur naturally by increasing some and decreasing others. It also alters the ecosystem to allow the development of invasive plants that have potential for creating residue situations. Living residues consist chiefly of understory or defective trees not utilized at harvest, plus a variety of shrubby and herbaceous species that carry over from preceding stands as either remnant plants or stored seed. Nonliving residues, on the other hand, include unmerchantable logs, standing snags, coarse limbs, and a fine litter complex of twigs, foliage, and other small debris.

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[2] Edward J. Dimock 11. Assessment of animal damage in Pacific Northwest forests--a problem analysis and short-term program of research. Pacific Northwest Forest and Range Experiment Station, USDA Forest Service, 12 p., 1971.

Character, density, and distribution of residues can significantly affect the numbers and kinds of vertebrates that utilize forest sites. Thus, man has the opportunity to manipulate animal habitat by varying both harvesting and residue disposal techniques. Still unclear, however, is just what or how great the impact of certain practices will be as opposed to others. Until the interactions of harvesting, residues, animal populations, and animal damage undergo more intensive scrutiny, most observed impacts should be considered localized and short term. Due to the dynamic nature of forest ecosystems, long-term effects on different sites may vary widely.

ANIMAL POPULATIONS

Improvement of animal habitat is considered the most universal effect of radical forest disturbances caused by either nature or man. Unbroken expanses of mature, old-growth timber are limited in their capacity to sustain large numbers of animal species that depend, at least in part, upon the habitat afforded by pioneering stages of forest development. Wildlife managers, whose chief concern is the propagation and management of birds and mammals sought by sportsmen, generally concur that timber cutting has been the single tool most useful to man in enhancing habitat for game (Lauckhart 1957). Numbers of black-tailed deer in Washington, for example, are now thought to exceed by many times the populations during the days of pioneer settlement (Brown 1961). Thouqh such i'ncreases are to some extent a response to restrictions on unregulated hunting, they result chiefly from the altered habitat created by widespread fires and timber cutting. Logging of Douglas-fir forests in northwestern California has caused substantial increases in songbird populations and marked changes in avian species composition (Hagar 1960). Similarly, habitats for forest game birds such as ruffed grouse, blue grouse, and band-tailed pigeons benefit from stages of forest succession short of climax types. Optimum habitat for these species is usually associated with transitional forest stages that contain mixed stands of softwoods, hardwoods, shrubs, and herbaceous vegetation.

Removal of old-growth forest cover is not necessarily beneficial to all mammals and birds. Some species depend solely or in large part on the food, cover, nesting sites, and other environmental necessities provided by climax or near-climax timber types. Douglas squirrels, for example, seldom stray far from conifers of cone-bearing age that provide a staple food source in the form of tree seed (Hooven 1969). Certain other species are quite specialized and cannot readily adapt to the radically altered environment caused by removal of mature timber. The red tree mouse--a small arboreal, microtine rodent--relies almost exclusively on the live crowns of Douglas-fir trees for its complete habitat needs in the humid, coastal forests of Oregon (Hamilton 1962). Various species of voles and shrews apparently find the heavy duff and litter layers under dense stands of old growth untquely suited to their ecological requirements and may respond to overstory removal by local population declines (Hooven 1969). Working in old-growth Douglas-fir forests of northwestern. California, Tevis (1956c) found that logging increased numbers of white-footed and big-eared mice, Townsend chipmunks, dusky-footed wood 'rats, digger squirrels, chickarees, gray squirrels, and brush rabbits; but decreased numbers of Trowbridge 'shrews, red-backed mice, flying squirrels, and shrew-moles. However, different small-mammal population trends may occur in other timber types. Harris (1968) concluded that clear-cutting in coastal forests of Alaska *(Picea sitchensis* Zone) doubled shrew populations, increased vole populations sixfold, and decreased deer mice populations by six times. Though not well-documented, the habitat requirements for a number of small insect- and seed-eating birds may depend to a major degree on the presence of mature timber for foraging, nesting, and avoiding predators (Marshall 1971). Likewise, some large raptorial birds, such as hawks and eagles, are known to depend upon habitats associated with mature timber types for successful nesting and rearing of young (Anderson 1971, Reynolds 1971).

The gradual conversion of old-growth forests to younger stands managed on relatively short rotations may ultimately impoverish habitat for some birds and mammals. However, over large areas, the changes are gradual and ameliorated by mixtures of old and young stands that characterize most sites where timber is managed for commercial purposes. Moreover, preservation of large acreages in parks, wildernesses, and various classes of wild and natural areas will insure perpetuation of the relatively few species that might be endangered due to any habitat deterioration from extensive timber harvesting, Such dangers are largely speculative and should not be allowed to obscure the fact that regulated timber harvesting enhances habitat for far more mammals and birds that it does not.

EFFECTS OF LIVING RESIDUES

Living residues resulting from remnant vegetation after logging exert mostly favorable effects on animal populations. Depending on composition and density, such residues afford varying amounts of food and cover for both mammals and birds. Residual plants can be of pronounced importance after clearcutting--often temporarily providing the only available source of forage. The progression of successional stages can also intensify this effect if living residues supply the nucleus for a dominant, seral shrub cover that develops after logging. In the more humid forests west of the Cascade Range, species typically regenerating from living residues include suck shrubs as salal, vine maple, thimbleberry, and trailing blackberry--all important for wildlife food and cover. In the drier habitats that characterize ponderosa pine forests, understory shrubs such as bitterbrush, an important browse species, may respond favorably to the release effected by timber harvest.

Unfavorable effects of living residues are generally few. Certain remnant species may effectively crowd out others that are more desirable for wildlife food but, in so doing, may provide improved cover. As succession progresses and specific residual shrubs assume a dominant role within their vegetative associations, the resulting dense cover may actually impede movements of large animals. This effect is generally not serious with big game but can be of concern on range habitats used by domestic stock. Similarly, plants that vigorously regenerate from stored seed may offer good habitat to only a limited number of wildlife species. The temporary predominance of salmonberry after cutting in Sitka spruce-western hemlock forests is a good example.

EFFECTS OF NONLIVING RESIDUES

Accumulations of nonliving debris comprise the most visible aftermath of timber harvesting. Their character and appearance vary with timber type, age of stand, and method of cutting. In any case, nonliving residues and their treatment, for at least a brief period after logging, probably assert a greater impact upon animal populations than do living residues.

Nonliving residues that follow logging in both the ***Picea sitchensis*** and ***Tsuga heterophylla*** Zones are superficially similar and often large in volume. Clearcutting is the most common form of harvest in the timber types occurring there, and debris from defective old-growth stands may easily exceed 100 tons per acre (224 metric tons per hectare) (Dell and Ward 1971). A recent trend toward partial cutting in some stands has served to reduce the volumes of debris that occur all at once on specific sites, and gradually improving utilization standards also help to lessen the incidence of extreme accumulations. Mature timber of younger age classes is normally less defective and produces correspondingly less residue. Thinning of young-growth timber may yield widely varying amounts of slash depending upon type of thinning and age class.

Past adherence to variations of selective cutting in the relatively open timber types of the ***Pinus ponderosa*** Zone has led to substantially lighter volumes of nonliving debris in these types. However, the increasing use of clearcutting in conjunction with artificial reforestation on some ownerships has augmented the problems of residue accumulation and disposal--particularly in timber types containing understories of marginal merchantability.

Effects of nonliving debris are mostly favorable to the wide spectrum of animals whose habitat is improved by timber harvest. Since most small mammals and birds are vulnerable to predation by hawks, owls, weasels, coyotes, and other species, the escape cover, afforded by residual slash enhances the already improved habitat. Clearcutting will most readily encourage rapid population increases if food and cover become simultaneously available. The presence of slash has improved habitat, for even those species, such as deer mice, that normally do not require dense cover (Hoffer et al. 1969). Slash also provides favorable nesting habitat for small birds--with ground-nesting species taking advantage of slash piles and hole-nesting species utilizing available snags.

Slash may also serve either directly or indirectly as a source of forage. Both coarse and fine residues are rapidly invaded by a variety of insects avidly sought as food by many small birds and mammals. Furthermore, fresh slash itself may also provide excellent forage for larger mammals, if only for a temporary period. Hardwood slash has been observed to be an important source of browse for white-tailed deer on right-of-way clearings in Pennsylvania (Bennett 1962); and both deer and cottontail rabbits readily feed upon apple prunings in the same State area (Morton and Sedam 1938). Studying the utilization of maple and birch residues in Maine, Alkon (1961) found that white-tailed deer preferred slash from wintertime logging over that produced before leaf fall. In western Washington, I have also observed heavy foraging on winter-produced Douglas-fir slash by both black-tailed deer and snowshoe hare.

Although large concentrations of slash can somewhat deter big-game use of cutover lands, moderate concentrations can give deer and elk a competitive advantage over livestock using the same range. Reynolds (1966a, 1969) noted that undisturbed slash was associated with greater use by mule deer and lesser use by cattle in ponderosa pine forests of the Kaibab Plateau.

Detrimental aspects of nonliving residues probably affect big game and domestic stock more than other animals. Two effects are paramount. Dense slash can simultaneously inhibit production of preferred browse plants as well as their accessibility to the animals that browse them. As inferred above, cattle have greater difficulties in utilizing ranges with undisposed slash than do deer or elk. The physical hindrance on cattle imposed by nonliving residues has been noted in a variety of ponderosa pine types (Pearson 1923, Reynolds 1969, Glendenning 1944). Slash piles resulting from sanitation logging in mixed conifers in northeastern Oregon have also been shown to impede cattle movements, thereby negating the benefits of browse that had been improved by timber harvesting (Young et al. 1967). Restricted elk use of cutovers by dense, uniformly distributed slash has been observed by Swanson (1970) in the coastal forests of western Oregon. Likewise, slash residues evidently deterred deer use temporarily after strip cutting in Colorado (Wallmo 1969).

Similar unfavorable effects of nonliving residues can be experienced by other animals but are considerably less significant. Perhaps the greatest single effect is depression of forage production by large volumes of debris. Habitat factors unrelated to the capacity of a site to produce forage can also be adversely affected. The loss of drumming sites for ruffed grouse in Minnesota due to logging slash (Gullion et al. 1962) may suggest similar parallels in the Northwest.

EFFECTS OF RESIDUE TREATMENT

In a broad sense, treatment of residues after timber harvest has a twofold impact. First, the influence of nonliving debris is altered and mostly reduced either by combustion, rearrangement, or pulverization. Second, the complex of living residues is sufficiently modified to measurably affect all parts of the ecosystems already altered by logging. As pointed out by Dyrness (1965), history of disturbance may be at least as important as preceding vegetative composition in determining subsequent plant distribution. Greatest impacts are generally immediate and mostly decline as stages of ecological succession advance (Yerkes 1960).

Responses by highly mobile animal populations to residue treatment are more subtle and difficult to evaluate than responses by more stationary elements of the ecological community such as plants. Nonetheless, substantial responses do occur. Effects are for the most part transitory, however, but semipermanent impacts are at least possible for some animal species. Essentially, changes in availability of a balanced complex of food and protective cover will govern the extent to which animal populations will be affected by residue treatment. Hence, the more radical the changes effected by treatment the more pronounced and lasting will be their effects.

Burning

The commonest residue treatment following timber harvest in either humid or more xerophytic forest types of the Northwest is prescribed burning. Since burning may induce both chemical and physical changes upon forest soil as well as reduce concentrations of both living and nonliving matter, it can also be the most drastic of residue treatments. Such an effect is not inevitable, however, since burning conditions vary, and partial or incomplete combustion may result in less pronounced changes than those produced by other treatment alternatives.

For disposal of logging slash, two principal burning options are open to the forest manager, and his choice between broadcast burning and some form of piling and burning depends upon timber type, age class, amount of residue, and sometimes the whim of the decisionmaker. Clearcutting is usually followed by broadcast burning in the more humid, coastal timber types but may be followed by some combination of piling and burning. The latter method is more commonly used in ponderosa pine timber types. When residue disposal is needed after thinning or partial cutting, the piling and burning method is also the normal choice.

Abatement of woody debris is the most immediately obvious consequence of burning. The change is directly advantageous to large mammals if untreated residues are large enough in volume to restrict access and mobility; but other animals whose habitat is enhanced by tangles of coarse and fine residues are adversely affected. An often-lauded impact of burning is its tendency to set plant successional stages back even farther than the reversals brought about by timber harvesting itself. Beneficial consequences for big game, range stock, and some smaller animals are: (1) The pioneering stages of plant succession include shrubby and herbaceous species that may be more highly preferred as forage. (2) Numbers of plant species available as preferred forage may be augmented. **(3)** Total quantity of preferred animal foods may be increased. (4) Quality of preferred forage may be stimulated by the temporarily increased supply *of* nutrients (chiefly N and P) that are released by burning and made available for plant growth. (5) Reversion to pioneering plant stages may effectively prolong the period of optimum habitability for animals. However, not all mammals and birds benefit from a fire-altered ecosystem, and some refer the habitat afforded by unburned dead and living residues (Hooven 19695. Stimulation of certain site-dominating plants, such as species of *Ceanothus* and *Arctostaphylos* that germinate from stored seed following burning (Gratkowski 1961), is also a mixed blessing for animal populations. The resulting habitats, although favorable to a few animals, discriminate against others. Too, burning may improve conditions favorable to either natural or artificial regeneration of commercially desirable timber species. Since this goal is usually a prime objective of forest management, its rapid attainment is detrimental to those animals whose habitats are favored by more prolonged associations of seral shrubs and herbaceous cover. Similarly, the destruction of more tolerant understory trees through burning is ultimately unfavorable to animal species that prefer mixed over pure stands.

Though burning may improve access to seeds and other foods, successful reduction of residues by fire is probably more neutral than beneficial to most bird life. Access to existing forage is seldom limiting to avian species. In the Douglas-fir region of northwestern California, Hagar (1960) noted that Oregon juncos and winter wrens are particularly dependent on the resting and escape cover afforded by cull logs and other slash. Nevertheless, comparing songbird populations in underburned and nonburned stands of 20-year-old slash pine in southern Florida, Emlen (1970) found number and composition of resident species essentially the same. Counts of ground foraging birds were nearly identical, although tree foragers showed a slight but nonsignificant preference for burned habitat and shrub foragers for unburned. From a logical standpoint,, production of and accessibility to foods valuable to some game birds may be improved by burning. However, in the Pacific Northwest, as elsewhere, good habitat for game birds depends mostly upon a favorable balance of food and cover, and factors other than burning are normally more responsible for creating such a balance.

Small mammal populations are initially depressed when residues are radically reduced by burning (Lawrence 1966). Controlled broadcast burns following clearcutting over large areas are most notable in this respect and more nearly approach the impact of uncontrolled wildfires. Piling and burning, on the other hand, may have negligible effects on small mammal populations if the environment already disturbed by logging is little altered by burning itself. Despite initial population declines, however, recovery by some species is almost immediate. Hooven (1969) in west-central Oregon, Tevis (1956a) in northern California, and Moore (1940) in western Oregon and Washington refer to the rapid recovery of deer mouse populations that may within a few months exceed levels prevailing before broadcast burning. Other small mammals, such as some voles and shrews, may require many years before populations will rebuild to levels equal to those before burning. Shrew populations, for example, can be virtually wiped out by debris burning (Moore 1942). These animals evidently suffer from the loss of protection formerly provided by logging debris and seem unable to adjust to cleanly burned conditions (Hooven 1969), but populations begin to rebuild slowly after several months (Moore 1940). Similar observations have been made in jack pine types of Minnesota (Ahlgren 1966); in a 3-year study, burning of slash appeared to favor deer mice, but red-backed mice and least chipmunks preferred the denser habitats associated with unburned slash. In general, all small mammals need at least moderate adjustment periods after fire, but some have the potential for quickly taking advantage of any habitat improvements caused by burning.

Prescribed burning is the cheapest and most widely recommended tool for improving big-game and livestock ranges in various parts of the United States (Leopold 1950). Documentation of its beneficial effects in the Pacific Northwest and adjacent areas has encompassed a variety of timber types: Douglas-fir forests of western Oregon (Swanson 1970, Harper 1971), Douglas-fir and grand fir forests of Idaho (Pengelly 1963; Lyon 1966; Leege and Hickey 1971; Leege 1968, 1969), Douglas-fir forests of western Montana,[3] and ponderosa pine forests in California (Biswell 1960). The favorable impact of residue burning on habitats for deer, elk, and livestock is discussed by Garrison and Smith (1974) in greater detail. However, an inference applying equally well to all forest types in the Pacific Northwest may be drawn from the conclusions of Harper (1971) who appropriately cautions:

> Even though, in some cases, burning enhances forage production, it is misleading and incorrect to state that widespread slash burning will increase production on all sites. The physical characteristics of each area, including soil type and depth, slope, exposure, moisture and other factors make each site different in its vegetative response to burning.

Optimum benefits often accrue in vegetative associations that are inherently least productive for forage; and, contrarily, where forage production is inherently high, least benefits may be expected.

Mechanical Treatment

Reduction, modification, and rearrangement of residues by mechanical means are alternatives to burning that will have increasing application in future forestry practice. Use of such methods has often been complementary to and in conjunction with the use of fire--e.g., machine or hand piling in preparation for burning. However, mechanical methods have been tried purely as alternative

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3/ Ralph A. Warner. 'Some aspects of browse production in relation to timber harvest methods and succession in western Montana. M.S. thesis, University of Montana, Missoula, 74 p., illus., 1970.

treatments. Included are such techniques as lopping and scattering of unmerchantable treetops, windrowing of dead and living debris, chipping or mashing of residues with heavy equipment, yarding of unmerchantable material for possible utilization, and even burying of slash for disposal of concentrated debris. Because such methods are relatively costly, and many are not even feasible on steep ground, their use has been limited. Moreover, the effects on animals of strictly mechanical treatment are not well documented.

From a logical standpoint, many effects of mechanical treatment should be similar to those caused by burning, though chemical changes and subsequent plant responses due to combustion itself would be lacking. The physical reduction of dense debris concentrations by crushing and chipping should be beneficial to large animals if it eases restrictions on their movements or access to forage. Smaller animals, on the other hand, would not benefit from the removal of needed escape cover. Windrowing has the potential advantages of both facilitating big-game and livestock movements and creating escape cover suitable for some smaller animal species. However, temporary destruction of forage and disruption of runways and burrow systems by the heavy equipment commonly used may partially nullify these advantages. Burying debris probably has a similar impact to windrowing, but reducing physical obstacles without providing compensating cover would likely prove less advantageous to animal populations as a whole.

Experience in western Oregon suggests that soil disturbance associated with operation of crawler tractors in logging Douglas-fir on high sites can significantly improve forage for some big game. The same benefits would presumably accrue from mechanical treatment of residues with heavy equipment. A high degree of soil scarification initially depressed but ultimately enhanced the production of preferred elk forage in both sword fern-wood sorrel and rhododendron-Oregon grape communities (Harper 1971). Considered high- and low-producing habitats, respectively, each type produced more preferred forbs and grasses and less nonpreferred shrubby species 5 years after disturbance. Further, the improved forage conditions persisted for 10 years or more after logging. In an allied comparison of burning and scarification effects, burned sites produced less total cover than untreated sites, but a higher proportion of preferred species; scarified sites produced more total cover than untreated, and also a higher proportion of preferred species.

Experience in other timber types can be either parallel or conflicting. Moderate soil disturbance in mixed coniferous forests of northeastern Oregon evidently improved forage conditions for cattle, but heavy disturbance depressed production by slowing natural revegetation (Young et al. 1967). In this case, machine piling of slash also impeded cattle movements and largely offset forage gains produced by sanitation logging. Reynolds (1966a) reached similar conclusions in ponderosa pine forests of the Kaibab Plateau. Although slash treatment by bulldozer piling and burning did not increase herbage production, it did augment cattle use--whereas deer use remained greater in untreated slash. Moreover, in Douglas-fir and grand fir types of the northern Rocky Mountains, Pengelly (1963) believed that bulldozing slash and burning it in piles would be less effective than broadcast burning in improving habitat for white-tailed deer, mule deer, and elk. In white spruce forests of western Alberta, scarification after logging retarded big-game forage production and utilization for 1 to 2 years compared with nonscarification (Stelfox 1962). Furthermore, forage production remained depressed 5 years later. Similarly, site preparation with rolling choppers on sandhill sites in Florida decreased forage for game species and substituted no food plants of comparable value (Hebb 1971).

Chemical Treatment

Despite current environmental concerns, treatment of living and nonliving residues with chemicals has both proven and hypothetical values, respectively, for hastening and protecting the growth of regenerating forest crops. One option entails the use of herbicides to release desired tree regeneration from overtopping or competing brush. A second option, the practicality of which is presently more conjectural than demonstrable, is the use of multipurpose chemicals to act as fire retardants, hasten slash breakdown, and benefit tree growth incidentally through fertilization. Regarding treatment effects on animal populations in forest habitats, little is known about the first option, and nothing about the second.

Depending on the chemical formulation used and the type of residue treated, every herbicide application probably has both positive and negative impacts on bird and mammal habitats. Though documented evidence on beneficial effects is not overwhelming, herbicides have been used operationally for the express purpose of improving game habitat in low-value timber types resulting from logging. For example, herbicide applications have been deemed beneficial for sharp-tailed grouse and white-tailed deer on hardwood-conifer scrublands in Michigan (Ammann 1963) and Wisconsin (Hartman 1956). Studies also suggest that herbicides can be more effective than burning in stimulating a preferred species of deer browse, such as mountain maple, in Minnesota (Krefting et al. 1956); and that aerial treatments can consistently and effectively increase browse production and deer use in a variety of habitats (Krefting and Hansen 1969). However, Goodrum and Reid (1956) seriously question the wisdom of extensive herbicide use in the South to convert low-value hardwoods to southern pine species; and they cite deleterious effects on wildlife habitat. Study results elsewhere also have negative implications. Herbicide treatments failed to stimulate browse production on big-game winter ranges in northern Idaho and even reduced or eliminated preferred browse species (Mueggler 1966, Lyon and Mueggler 1968). In some instances, nevertheless, an unfavorable impact on animal habitat may be the desired objective of chemical treatment--e.g., the herbicide-induced reduction of food supply for plains pocket gophers on rangelands in Colorado (Keith et al. 1959, Tietjen et al. 1967).

Though herbicide treatments are normally aimed at reducing the competition afforded by residual shrubs and low-value trees to desired timber species, their side effects have implications of value for management. The intentional manipulation of animal habitats with chemicals may prove useful if effects on animal habitats and tree growth are compatible and complementary. Preliminary studies of herbicide effects on Douglas-fir cutovers in western Oregon suggest that the abundance and species composition of small mammals can be altered with no acute impact on total populations (Borrecco et al. 1972). Further, use by black-tailed deer of the same cutovers was somewhat reduced by treatment--a possible benefit to tree growth. On the other hand, Harper (1971) presents tentative evidence that herbicide release did not benefit tree survival or growth among Douglas-fir seedlings growing in prime elk habitat of coastal Oregon. He speculates that immediate effects of extensive spraying over large acreages may be unfavorable to both elk and Douglas-fir; but he also reasons that spraying living residues in older cutovers may encourage production of available browse and increase use by elk. The use of herbicides on living residue is more fully discussed by Gratkowski (1974).

The potential of treating nonliving residues with nutrient-rich fire retardants has not as yet been adequately explored. However, if forage species are successfully enhanced in amount and quality, net benefits for some wildlife are likely.

ANIMAL DAMAGE

Mammals that typically cause damage in regenerating forests have been amply documented and were extensively reviewed. by Radwan (1963). Additional references pertinent to problem animals and damage situations in the Pacific Northwest and elsewhere throughout North America would include: *General* (Black 1970, Canutt 1969, Crouch 1969b, Dimock and Black 1969, Heacox and Lawrence 1962, Hermann 1969, Hooven 1970); ***Seed eaters*** (Abbott 1966, Adams 1947, Gashwiler 1969, Krull 1970, McGregor 1958, Radwan 1969, Shearer and Schmidt 1971, Schmidt and Shearer 1971); ***Foliage feeders*** (Bergerud and Manuel 1968, Cook 1946, Crouch 1968, Crouch and Paulson 1968, Fowle 1960, Gessel and Orians 1967, Godin 1964, Gurchinoff and Robinson 1972, Janzen 1962, Mitchell 1964, Read 1971, Richards and Farnsworth 1971, Tierson et al. 1966, Wakeley 1970, Walters and Soos 1961); ***Root and stem feeders*** (Crouch 1971, Hermann and Thomas 1963, Oliver 1968, Tevis 1956b).

The correlation between animal damage and animal populations would seem to be close. For the most part, it undoubtedly is--but only for mammals and birds that significantly reduce or delay forest yield by their activities. Obviously, not all animals do. Despite the considerable number of species known to forage on tree seed or to use young trees for food and occasional nesting material, species causing measurable economic damage are relatively few. A tentative listing of vertebrates having the most serious economic impact on Douglas-fir and ponderosa pine in the Pacific Northwest would include:

Species	Food item most relevant to damage
Douglas squirrel	Seed
Deer mouse	Seed
Yellow pine chipmunk	Seed
Golden-mantled ground squirrel	Seed
Oregon junco	Seed
Varied thrush	Seed
Black-tailed deer	Foliage
Mule deer	Foliage
Elk	Foliage
Snowshoe hare	Foliag'e
Blue grouse	Foliage
Mountain beaver	Foliage
Northern pocket gopher	Roots, bark
Porcupine	Bark
Black bear	Sapwood

In addition, each of the above species may benefit man by its activities or presence within the forest ecosystem. Cacheing cones that may assist seed collectors, burying seed that may contribute to natural tree regeneration, improving soil tilth that may enhance tree growth, or simply providing enjoyment that may benefit sportsmen and recreationists--all are recognized phenomena having either practical or amenity value. Weighing the positive and negative contributions of each species, therefore, becomes a highly subjective and probably fruitless endeavor. In short, animals can and do damage forest crops. Moreover, the animals that do so most commonly expand their populations following man's timber harvest activities that lead to residue situations.

What, then, are the effects of residues and their treatment on animal damage per se?

Unfortunately, the effects of either living residual plants or woody debris on levels of animal damage are even less well documented than their effects on animal populations. Numbers of animals will vary to the extent that their habitats are either enhanced or degraded by residues and residue treatments. Accordingly, most inferences must be drawn from the assumed relationship implied previously--i.e., increases in populations of problem mammals and birds will likely initiate or intensify damage to forest crops. The relationship is only general, however, and cannot be assumed to be axiomatic. High populations of deer and elk do not always lead to acute browsing problems, for example, (Hines 1963). Relatively low numbers of deer mice, on the other hand, may seriously limit natural regeneration of preferred tree species, and almost completely nullify artificial seeding efforts. Moreover, low populations of seed eaters sometimes consume more tree seed than high populations (Moore 1940).

EFFECTS OF LIVING RESIDUES

In providing both forage and cover, living residues are chiefly beneficial to nearly all birds and mammals considered problem species--especially those that utilize tree and shrub foliage. Though still considerable, advantages are probably less for seed-eating animals, depending upon the food and cover requirements of specific mammals and birds. Immediate benefits are probably least for subterranean root feeders, namely pocket gophers, and also bark and sapwood feeders that prefer habitats associated with more advanced successional stages.

Though not strictly a living residue in the sense defined here, the forest edge bordering harvested timber has a profound effect on some problem species. Many, whose habitats are temporarily worsened by clearcutting, will retreat to forest edges for necessary cover where the interface between cut and uncut timber is even more suitable habitat than either alone. One notable example is snowshoe hare; and it will range extensively in open habitats if suitable escape cover is available (Hooven 1969). Townsend chipmunk, a seed eater, also prefers edge habitats immediately following timber cutting (Hooven 1973). The effect of distance from mature timber on elk use and damage to Douglas-fir seedlings was intensively studied by Harper (1971), who found that elk damage decreased as distance from timber edge increased. Similarly, Reynolds (1966b) found that mule deer and elk ceased to use clearcut openings beyond 1,200 and 1,400 feet (366 and 477 meters), respectively, from timber edges.

The attractiveness of shrubby residues as forage can influence the degree of damage to tree regeneration growing in close proximity (Gratkowski 1967). Cover of trailing blackberry, a species highly preferred by black-tailed deer, led to increased damage on associated Douglas-fir seedlings in a northwest Oregon study (Crouch 1968); however, he also found that incidence of damage to tree seedlings varied inversely with increasing height of associated shrubby cover. Similar protective effects of living residue cover have been noted elsewhere. Dimock (1964) found that tall, dense western bracken measurably protected planted Douglas-fir from snowshoe hare and black-tailed deer in western Washington. Later results from the same study (Dimock 1970) showed that deer did not readily browse seedlings until they exceeded 3 feet (1 meter) in height. Dense salmonberry in western Oregon was found to have a similar effect on deer,[4/] although experience elsewhere has shown that salmonberry habitats can greatly increase the probability of rabbit and hare clipping on interplanted Douglas-fir.

EFFECTS OF NONLIVING RESIDUES

Unmerchantable logs, snags, limbs, and litter provide favorable cover--mainly for small mammals and birds. As pointed out earlier, fresh slash may also provide temporary forage for such mammals as hare, rabbits, and deer. Hence, the presence of nonliving residues can increase the probability of damage to young trees by small animals if the woody debris substantially improves animal habitats. Mitchell (1950) observed that planting trees 5 to 20 feet (2 to 6 meters) from brush piles was necessary to lessen damage by brush rabbits on western Oregon sites. Increased potential for damage by snowshoe hare in habitats with prominent slash piles can also be expected.

From the standpoint of animal damage, physical protection from animals is probably the predominant effect of nonliving residues upon Douglas-fir and ponderosa pine regeneration. Though it is doubtful that birds are appreciably deterred by slash in their foraging for tree seed, the presence of fine debris allows many seeds to go undetected in protected locations that may favor subsequent germination and growth.

The intentional use of lightly piled slash to protect ponderosa pine seedlings from big-game browsing has been common practice for several years on some National Forests in the Pacific Northwest. In ponderosa pine types of northern Arizona, Arnold (1953) observed that a light scattering of slash favored establishment of pine seedlings--presumably by providing temporary protection from livestock. Grisez (1960) in Pennsylvania conclusively demonstrated that slash piles effectively protected regenerating hardwoods from deer browsing; and he also cited instances elsewhere in which slash had inadvertently given browsing protection (Pearson 1923, Little and Somes 1949), or loppings had been intentionally used for the same purpose (Clepper 1936). In northwestern Oregon, Crouch (1968) found that Douglas-fir seedlings planted on highly disturbed sites--those relatively free of logging debris--were more prone to browsing than those planted in undisturbed locations. Decreasing incidence of elk damage to Douglas-fir regeneration with increasing amounts of woody debris has also been shown in coastal western Oregon (Swanson 1970). Influence of residues on grazing animals is covered in greater detail by Garrison and Smith (1974).

4/ Hollis Howard Allen. The inter-relationship of salmonberry and Douglas-fir in cutover areas. Master's thesis, Oregon State University, Corvallis, 56 p., 1969.

EFFECTS OF RESIDUE TREATMENT

Although residue situations mostly benefit populations of problem animals, it may be inferred from the above that the presence of residues does not necessarily increase the occurrence or severity of animal damage to regenerating trees. The physically protective influence of both living and nonliving materials more often than not outweighs the adverse effects of improved habitat for problem animals. Hence, animal damage will generally be less in residue situations that remain untreated; and residue treatments will likely result in increased levels of animal damage to forest regeneration.

Though residue burning probably increases potential for animal damage, correlation between the two has not been plainly demonstrated or sufficiently studied. A recent opinion survey regarding animal problem areas on National Forests of Oregon and Washington 'indicated an association between burning and animal damage on 19 out of every 20 areas (Crouch 1969a). The ratio may be high, however, simply due to the commonness of burning as a residue disposal tool.

Disposal of slash to control rodents has been suggested as a means of protecting tree seed (Krauch 1945). Most recent evidence, to the contrary, suggests that slash burning increases populations of problem rodents and their predation on tree seeds. Broadcast burning also assures more efficient seed predation by birds, even though it may create a more favorable seed bed for germination. Since the immediate effects of fire are to create more open conditions, the likelihood that seedlings will be browsed by herbivores is greatly enhanced. Trees planted immediately after broadcast burning, for example, are virtually the only source of green forage on some cutovers until associated plants germinate or sprout. In coastal forests of the western Olympic peninsula in Washington, Gockerell (1966) concluded that browsing by elk and deer was much greater on burned than on unburned cutovers. Harper (1971) showed that serious elk damage to Douglas-fir seedlings was most likely to follow burning--i.e., 62 percent of most heavily damaged acres in coastal Douglas-fir types of western Oregon occurred on burned sites vs. 38 percent on unburned. Working on the same area, Swanson (1970) reached similar conclusions.

Mechanical treatment of residues poses much the same problems for tree regeneration as burning, and for similar reasons. Heavy equipment used to chip slash would probably have the net effect of increasing animal damage. Though escape cover and forage production might be temporarily decreased by a layer of chipped mulch, the increased exposure of tree seedlings would likely precipitate a greater incidence of animal-caused tree injury--especially by big game. In mixed conifers of northeastern Oregon, Young et al. (1967) observed that dense stands of bull thistle characteristically followed severe disturbance by heavy equipment and could thus attract tree-damaging rodents.

Windrowed slash, furthermore, provides the threat of increased damage by both large herbivores and smaller animals. Not only are tree seedlings more exposed to browsing mammals, but also to others, such as hares and rabbits, that readily take advantage of resulting slash piles. In any case, the net effect of mechanical residue disposal is to increase the damage potential for tree seed and seedlings.

Of all treatment options, the effects of chemical treatment on animal damage are least understood. Hermann (1969) has observed that dense brush fields of ceanothus, resulting from prior slash burning, can pose added problems, if herbicide spraying and subsequent residue piling create favorable habitats for rabbits and deer. Nevertheless, Zavitkovski et al. (1969) cited instances on upper-slope forests of the Oregon Cascades in which herbicidal control of ceanothus on large areas successfully reduced snowshoe hare populations and decreased clipping on planted conifers. Treatment of small areas, on the other hand, had no measurable effect on animal damage. Increasing the chances for heavy deer damage to planted trees does not imply that such damage invariably occurs, however, and I have observed effective herbicide release of existing reproduction without concomitant animal problems. Harper (1971) noted that, although herbicide spraying did not increase elk damage to Douglas-fir seedlings, it did indirectly decrease their survival. He speculates further, though, that widespread spraying may be detrimental to Douglas-fir by causing elk to shift browsing pressure toward regenerating trees on the same or adjacent sites. Borrecco et al. (1972) also show that browsing of Douglas-fir by deer was not significantly altered by limited herbicide application.

Using herbicides to treat living residues may have the best potential for minimizing vegetative competition with desired tree species and stimulating production of accessible forage without appreciably increasing animal damage. Fire retardant chemicals, which may improve nutritional quality of forage species and hasten breakdown of nonliving residues, probably have no marked effect on animal damage.

CONCLUSIONS

Not surprisingly, environmental factors that affect populations of problem animals--a valuable, mobile, and highly adaptable part of the forest ecosystem--are exceedingly complex. The literature attests to the variability of animal responses to forest residues and treatment options. A few general conclusions about effects of residues and residue treatments on animals most likely to damage regenerating timber crops are:

1. By providing both food and cover, living residues usually favor increases in populations of seed and seedling foragers.

2. By chiefly providing cover and some food value, nonliving residues essentially improve habitats for most animals.

3. Through altering, but not eliminating, both living and nonliving residues, most residue treatments ultimately enhance habitats--especially for large animals.

4. By improving habitats for most animal species, living residues increase potential for animal damage; but, by physically obscuring regenerating tree crops from predators, they may essentially deter the occurrence of most serious damage problems.

5. By similarly protecting seed and seedlings of desired tree species, nonliving residues more generally inhibit than promote the occurrence of animal damage.

6. By enhancing even further the animal habitats already improved by residues, most residue treatments increase the probability of animal damage to seed and seedlings through removing protection from and prolonging exposure to increased numbers of problem animals.

RESEARCH IN PROGRESS

The author is aware of only five current studies which deal directly with effects of forest residues and their treatments on animal populations and/or animal damage in the Pacific Northwest. These are:

Study Title: Biological succession of animals and plants associated with clearcutting an area in western Oregon

Principal Investigator: Edward F. Hooven

Agency: School of Forestry, Oregon State University

Location: Blue River Ranger District, Willamette National Forest, Oregon

Study Description: The effect of slash treatment on small mammal populations

Study Title: Environmental manipulation techniques

Principal Investigator: William W. Hines

Agency: Oregon State Game Commission

Location: Elliott State Forest, Coos and Douglas Counties, Oregon

Study Description: Effects of herbicide spraying as a silvicultural tool on elk forage production, forage quality, and elk use of areas

Study Title: Impact of herbicides on western forest ecosystems

Principal Investigator: Michael Newton

Agency: School of Forestry, Oregon State University (McIntire-Stennis support)

Location: Western Oregon and Washington

Study Description: Management of habitat with herbicide and response of plant and animal communities to habitat alteration

Study Title: Response of animals to herbicide-induced vegetational changes

Principal Investigator: Hugh C. Black

Agency: School of Forestry, Oregon State University

Location: Medford District, Bureau of Land Management, western Oregon

Study Description: Effects of herbicide-induced vegetational changes on the abundance and feeding activities of pocket gophers and on the composition and abundance of small mammals

Study Title: Wildlife response to vegetation manipulation

Principal Investigator: Richard D. Taber

Agency: University of Washington

Location: Western Washington

Study Description: Effects of right-of-way establishment and manipulation on wildlife populations

RECOMMENDED RESEARCH

Animal damage is only one of many constraints upon rapid and successful regeneration of desired timber crops. Moreover, defining damage levels critical to attainment of that goal is difficult, tenuous, and still highly subjective. Decisions regarding the necessity and means to cope with residue situations must be governed by a host of considerations dealt with elsewhere in this Compendium. However, a few tentative speculations and recommendations for future study follow.

Perhaps the only residue treatments likely to substantially reduce animal problems would be those sufficiently drastic to result in extensive deterioration of animal habitat. What these might be is conjectural, and, even if found and developed, their use would be unfeasible due to excessive cost, environmental considerations, and other undesirable side effects.

At the other end of the spectrum and strictly for purposes of mitigating or preventing potential animal problems, a policy of nontreatment would likely pay handsome dividends. However, some treatment of residues is normally essential to maintain site productivity at levels that balance plant and animal resources in ways satisfying to both commercial and environmental interests.

Treatment methods that alter residues the least--although still meeting objectives of reducing fire hazard, lessening waste, and alleviating brush competition--seem to have most practical possibilities for minimizing animal problems. Burning, with its variations, is probably least adaptable for this purpose. Mechanical methods that achieve disposal goals with a minimum of site disturbance and residue alteration, might simultaneously change animal habitats little and yet preserve sufficient residues for seed and seedling protection. Finally, adaptation and development of herbicide treatments to combat competition from living residues may be one of the most promising approaches to harmonizing animal populations and timber stand regeneration.

Current environmental considerations have spawned a growing interest in alternative silvicultural systems that lessen the unsightliness, site degradation, and waste associated with traditional methods of timber harvest and residue disposal— chiefly clearcutting and broadcast burning. Accordingly, future forest practices may be expected to include increasing varieties and combinations of timber cutting and residue disposal methods. Though startling breakthroughs in management of animal habitat or reduction of animal damage are unlikely to emerge, extensive research to monitor the effects of changing practices on both parameters should be encouraged and closely integrated with other research objectives. However, intensive research unilaterally designed to alter residue management in ways that maximize wildlife habitat and minimize animal damage seems hardly justified.

CHECKLIST OF PLANTS AND ANIMALS

Common name	Scientific name
PLANTS	
Bitterbrush	*Purshia tridentata*
Blackberry, trailing	*Rubus vitifolius*
Bracken, western	*Pteridium aquilinum pubescens*
Ceanothus	*Ceanothus* sp.
Douglas-fir	*Pseudotsuga menziesii*
Fern, sword	*PoZystichwn munitum*
Fir, grand	*Abies grandis*
Hemlock, western	*Tsuga heterophylla*
Manzanita	*Arctostaphylos* sp.
Maple, mountain	*Acer spicatum*
Maple, vine	*Acer circinatum*
Oregon grape	*Mahonia nervosa*
Pine, jack	*Pinus banksiana*
Pine, ponderosa	*Pinus ponderosa*
Pine, slash	*Pinus elZiottii*
Rhododendron	*Rhododendron macrophyllum*
Salal	*Gaultheria shalZon*
Salmonberry	*Rubus spectabilis*
Spruce, Sitka	*Picea sitchensis*
Spruce, white	*Picea glauca*
Thimbleberry	*Rubus parviflorus*
Thistle, bull	*Cirsium vulgare*
Wood sorrel	*OxaZis oregana*
MAMMALS	
Bear, black	*Euarctos americanus*
Beaver, mountain	*Aplodontia rufa*
Chipmunk, least	*Eutamias minimus*
Chipmunk, Townsend	*Eutamias townsendii*
Chipmunk, yellow pine	*Eutamias amoenus*
Coyote	*Canis latrans*
Deer, black-tailed	*OdocoiZeus hemionus columbianus*
Deer, mule	*OdocoiZeus hemionus*
Deer, white-tailed	*Odocoileus virginianus*
Elk	*Cervus canadensis*
Gopher, northern pocket	*Thomomys talpoides*
Gopher, plains pocket	*Geomys bursarius*
Hare, snowshoe	*Lepus americanus*
Mouse, big-eared	*Peromyscus truei*
Mouse, deer (white-footed)	*Peromyscus maniculatus*
Mouse, red tree	*Phenacomys longicaudus*
Mouse, red-backed	*Clethrionomys* spp.

Common name	Scientific name
MAMMALS (continued)	
Porcupine	*Erethizon dorsatum*
Rabbit, cottontail	*SyZvilagus floridanus*
Rabbit, brush	*SyZvilagus bachmani*
Shrews	*Sorex* spp.
Shrew, Trowbridge	*Sorex trowbridgii*
Shrew-mole	*Neurotrichus gibbsii*
Squirrel, digger	*OtospermophiZus beecheyi*
Squirrel, Douglas (chickaree)	*Tamiasciurus douglasii*
Squirrel, flying	*Glaucomys sabrinus*
Squirrel, golden-mantled ground	*CallospermophiZus* spp.
Squirrel, gray	*Sciurus griseus*
Voles	*Microtus* spp.
Weasels	*Mustela* spp.
Wood rat, dusky-footed	*Neotoma fuscipes*
BIRDS	
Grouse, blue	*Dendragapus obscurus*
Grouse, ruffed	*Bonasa umbellus*
Grouse, sharp-tailed	*Pedioecetes phasianelZus*
Hawks and eagles	Accipitridae
Junco, Oregon	*Junco oreganus*
Owls	Tytonidae, strigidae
Pigeon, band-tailed	*Columba fasciata*
Thrush, varied	*Ixoreus naevius*
Wren, winter	*Troglodytes troglodytes*

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HABITAT OF GRAZING ANIMALS

George A. Garrison and Justin G. Smith

ABSTRACT

Residues from Zogging or thinning operations in Pacific Northwest timber types have varied effects on grazing animal habitat including occupation of ***growing*** *site, obstruction of access to forage and water, and modification of the forest floor environment. Residue treatments that modify or remove excessive woody residues seem to favor production of forage. Some research has been done on plant ecosystem development after genera2 Zogging disturbances, but very little has been undertaken in the way of comparative study of residue treatment practices, particularly in reZation to grazing animal habitat.*

Keywords: Big game habitat--forage, access; livestock.

INTRODUCTION

Forest residues remaining on the ground after tree harvest or improvement cuts alter the habitat for grazing animals. The coarse or large diameter materials effect a long-term reduction in forage production; and large volumes of lighter materials impede access and movement of livestock and big game to forage and water for several years, although slash can provide some temporary escape cover for a variety of wild creatures. Residues and treatments of them also modify the microenvironment of the forest floor and may thus influence germination, growth, establishment, and secondary succession.

Amounts of untreated slash in a forest provide some indication of the impacts of slash and its treatment on range and environment for grazing animals. The major timber types are, of course, a primary variable in consideration of amount of slash initially generated. In the Pacific Northwest, the coastal Douglas-fir *(Pseudotsuga menziesii)* forests, when clearcut, can create as much as 227 tons of slash per acre (509 metric tons/ha) (Dell and Ward 1969), of which about 30 percent will be cull logs and other heavy materials (Dyrness 1965b). In the interior Northwest or so-called ponderosa pine *(Pinus ponderosa)* subprovince, logging slash for selectively logged lands is variously estimated at 12 to 40 tons per acre (about 27 to 90 metric tons/ha), and in patch cut areas slash can total 50 to 110 tons per acre (about 112 to 246 metric tons/ha) (Hall 1967) with 60 percent of this weight provided by material less than 4 inches (10.15 cm) in diameter (Sundahl 1966).

EFFECTS OF UNTREATED RESIDUES

Slash created by clearcut logging in coastal Douglas-fir forests of Oregon and Washington may be present to some degree on about 75 percent of the logging area (Dyrness 1965b). Computations from a report by Dyrness (1965a) show a decrease in cover of understory vegetation from about an average of 70 percent to about 10 percent. Then in a subsequent set of data within this report, a partitioning of slash and soil disturbance impacts on plant cover shows slash to be the major influence among logging disturbances. Species suffering the most loss in crown cover from the accumulation of heavy slash and logs and some soil disturbance included such important elk foods as vine maple *(Acer circinatum)*, salal *(Gaultheria shallon)*, and swordfern *(Polystichum munitum)*. Subsequent burning of the debris caused additional changes which will be discussed later. In a study of a similar forest type, Swanson (1970) related elk use of different sites to amount and distribution of logging residues. Heaviest use was noted on areas with moderate amounts of slash and where the distribution of it was patchy; lightest use on areas with large volumes and where it was uniformly distributed.

The forest types of the interior Northwest and inland Western United States are prime summer habitat for both domestic herbivores and big game. Several researchers have been interested in the effect of selection logging of ponderosa pine on understory vegetation. In eastern Oregon and Washington, Garrison and Rummell (1951) recognized the influence of coarse slash accumulations in long-term reductions of forage. They found that on a selection cut sale with skidding by crawler tractors, over 5 percent of the ground was covered with heavy slash and that over 21 percent was denuded of vegetative cover as a result of soil disturbance. They also reported a 33-percent reduction in cover of shrubby and herbaceous vegetation from the prelogging condition by the combined effects of slash of all sizes plus soil disturbance that had accrued during the first year after logging. In the Jeffrey *(Pinus jeffreyi)* and ponderosa pine area of northern California, Hormay (1940) reported a 19-percent reduction in forage from a combination of all types of debris and surface disturbance by skidding. For northern Arizona, Arnold (1953) found that combined sizes of logging slash occupied 13.2 percent of the harvest area.

The grand fir *(Abies grandis)* type of northeast Oregon only started to come under management in recent years, so many large trees are still found dying of root rot, heart rot, and major insect troubles; thus, of the 17-percent area in slash after sanitation logging, a high proportion consists of cull logs. And according to Young et al. (1967), the many large cull logs, although delimbed, were a serious obstruction to grazing animals.

Not all aspects of untreated slash are detrimental. Reynolds (1966) reported for northern Arizona that cattle droppings were more numerous on areas cleared of slash, whereas deer droppings were greater where slash was undisturbed. He speculated that slash presents a greater physical obstacle to cattle than it does to deer and that deer may feel more conspicuous in cleared areas, but size of opening influences this relationship. In relation to recovery of vegetation following logging in the pine type, Garrison [1961] reported that almost no tree seedlings lived through the seventh year on a deeply skidded trail unless site conditions were ameliorated by slash. Arnold (1953) observed in northern Arizona that when skid trails and other disturbed areas are reseeded, a light scattering of slash favored establishment of both grass and pine seedlings.

A large and significant slash problem also exists after precommercial thinning of suppressed overstocked stands of ponderosa pine in eastern Oregon and Washington. Not uncommon are stands of 2,000 to 18,000 stems per acre (about 4,940 to 44,470 stems/ha) whose diameters are still 5 inches (12.7 cm) or less and heights are usually under 21 feet (6.4 m) at 30 to 70 years of age. Some of these dense stands, if not impenetrable, provide good hiding cover for deer but very little shrubby and herbaceous forage in the understory. When thinned to 110 to 600 trees per acre (about 270 to 1,480 stems/ha), such stands produce enough slash to 'completely blanket the ground and discourage a favorable understory response to the opening of the tree canopy. This slash before reduction treatment is often 3 feet (about 1 m) or more deep (Dell and Ward 1969); and according to slash weight tables by Fahnestock (1968), the residue weights for stands of 3,000 to 5,000 stems per acre (about 7,400 to 12,350 stems/ha) are 35 to 45 tons per acre (about 78 to 100 metric tons/ha).

The most common complaint of livestock operators about precommercial thinning is the massive blockage of established stock trails to streams and water developments. The degree of slope and routing of these trails have a "tested design" and are important to both livestock and big game; thus, indiscriminate felling of thinnings across trails and lack of slash treatment are very disruptive to habits and needs of grazing animals.

EFFECTS OF BURNING RESIDUES

Burning slash has long been an accepted procedure following timber cutting in most forest types and is still effective and in use in spite of any contribution to air pollution. Burning obviously reduces the impact of woody debris as an obstacle to grazing animals, and it also influences composition of the vegetation that occupies the site in the process of secondary succession. The literature is extensive on the role of fire, particularly wildfires, in forest development (Ahlgren and Ahlgren 1960, Daubenmire and Daubenmire 1968, Franklin and Dyrness 1969, and others). Since the development of modern fire suppression methods, studies of fire effects have somewhat shifted to relating fires for slash disposal to plant succession and allied subjects. Information on slash fire influences is not abundant, but there are some important works on the topic.

Reid et al. (1938), working in the coastal Douglas-fir region, studied a large number of plots on clearcuts with different dates of slash burning and reburning; all plots were subjected to sheep grazing. They concluded that weeds, principally fireweed (*Epilobium angustifolium*), are prominent for a time after slash burning, and the weed stage under grazing use is followed by some growth of shrubs, such as vine maple and trailing blackberry, plus considerable amounts of various grasses and sedges. However, on areas of repeated burns or delayed burns, a rapid and militant encroachment of bracken fern (*Pteridium aquilinum pubescens*) was common even with grazing. As these authors acknowledge, the potential for grazing a patch cut of Douglas-fir or true fir forest is about 15 years. Various other authors state 18 to 20 years of grazing use before tree canopy closes in. Of course, continued harvests provide a progression of these temporary grazing areas.

Bailey (1966) described several habitats in clearcuts in the Douglas-fir region (*Tsuga heterophylla* Zone (Franklin and Dyrness 1969)) with and without effects of slash fires. Habitats of differing vegetal composition, aspect, slope position, etc., showed different responses to slash burning and subsequent use of big game. In the swordfern-wood sorrel (*Oxalis oregana*) habitat, the net response was generally more favorable to elk on burned than unburned cutover sites. For the maidenhair fern (*Adiantum pedatum*)-ladyfern (*Athyrium filix-femina*) community which is a high producer of elk, burning provides only a slight improvement in forage production. In contrast, burning in the rhododendron (*Rhododendron macrophyllum*)-Oregon grape (*Berberis nervosa)* and in the vine maple-Oregon grape communities greatly increases herb and shrub production.

Swanson (1970) and Harper (1971) studied elk use on the habitats identified by Bailey (1966). They concluded that (1) although burning reduces total vegetal cover and forage production for two or three growing seasons, the change in composition to dominance by herbaceous species becomes increasingly important to elk as favored feeding sites; (2) although unburned logged units have much higher vegetal cover for a year or two after logging, usable forage production on them diminishes at a more rapid rate than on burned areas; and (3) persistent grazing of burned sites tends to maintain dominance of desirable herbaceous species and discourage invasion of shrubby species which, in general, make less attractive habitat for elk.

Pengelly (1963) studied logging effects on deer habitat in the Douglas-fir and grand fir types of northern Idaho and concluded that slash burning often favors early establishment of seral shrubs, many of which are preferred forage species. He also reported preliminary studies indicated that broadcast burning of debris would foster heavier initial stands of preferred forage than would burning in piles.

In the grand fir study area (which Daubenmire and Daubenmire (1968) identified as the *Abies-Pachistima* habitat type), Pengelly found that logging had a negligible effect on shrub cover except where burning also occurred.

In the more xeric *Pseudotsuga-Physocarpus* habitat type of western Montana, Warner[1/] compared browse production logged areas with and without slash burning. He reported more than twice as much production on the burned site 4 years after burning and attributed most of the difference to increases in redstem ceanothus *(Ceanothus sanguineus)* and snowbrush ceanothus (*C. velutinus*). These species are noted for their ability to resprout after being burned, but they are limited to certain habitats.

The influence of fire on determination of grass and shrub understory composition in the pine type was evaluated by Daubenmire and Daubenmire (1968):

> Common opinion [that fire produces grass, not shrubs] is undoubtedly in error regarding the alleged role of fire in determining whether the undergrowth beneath the pine is dominated by shrubs or by grasses. ,There is unmistakable evidence that all undergrowth layers except the one consisting of the fire-sensitive *Purshia tridentata* regenerate immediately from underground organs after each fire. Rather than fire history, these subordinate layers reflect intrinsic differences in moisture, fertility and microclimate.

1/ Ralph A. Warner. Some aspects of browse production in relation to timber harvest methods and succession in western Montana. M.S. thesis, University of Montana, Missoula, 74 p., illus., 1970.

There is also considerable evidence that seed of shrub genera such as *Ceanothus* and *Arctostaphylos* can remain dormant but viable in duff and soil for long periods and be stimulated to germinate by heat (Gratkowski 1961). It is readily apparent then, that where these genera are now or have been prominent in pine understory, as for example in central Oregon, slash burning may enhance their status in the plant community or, at the very. least, maintain it.

In the pine type of eastern Washington, where Garrison and Rummell (1951) had been measuring logging effects and secondary succession, Garrison [1961] observed that burn treatment of logging slash resulted in 14-percent additional loss of vegetal cover beyond that lost from logging effects, the loss being mostly among grass and shrub species, but the fire appeared to stimulate a flush of forb growth. However, the additional damage attributed to burning was only temporary, and both grasses and shrubs were increasing 2 years later.

Relation of early day wildfire and prescribed burning to maintenance of rather open and highly grazeable ponderosa pine forests is widely acknowledged. But influence of small spot burns from treatment of piled pine slash seems to be temporary in changing species composition. Hard burned areas, however, will be slow in regaining original vegetation cover.

Much has been written on the fertilizing effect of wood ash in all timber types. Taber (1973) has summarized some of the literature on this and the often associated effects of overstory removal. The evidence seems to emphasize that the ash-fertilization effect extends only over the first year or two, whereas the effects of increased light from overstory removal may last about 10 years. Thus, in patch clearcuts that are broadcast burned after logging, we cannot completely partition the contribution of effects of opening the canopy and the fertilizing effects of ash, but their ultimate consequence is of some benefit to ground cover vegetation.

EFFECTS OF OTHER RESIDUE TREATMENTS

The rapidly growing concern over air pollution from slash burning has helped stimulate a search for other means of debris disposal. Various techniques have been tried including burying, chipping, rotary cutting, mashing, lopping and scattering, and application of chemicals to accelerate decomposition. Almost without exception, these alternatives to burning have been studied from the standpoint of economics and efficacy of residue reduction with little regard to their effect on understory succession or animal use.

The simple act of burying slash also often results in the burial of the valuable humus layer, the "A" horizon of the soil, the seed source in surface soil, and all the existing ground cover vegetation at the burial pit itself. Ground layer vegetation serves as erosion protection, forage producer for livestock and wildlife, and a nutrient sink for keeping soil nutrients available in the rooting zone for all forest vegetation. Burial of slash is rather catastrophic to the ground layer at the burial spot, yet probably has one value for wildlife, i.e., burrowing rodents often seem attracted to such works.

Chipping of slash and dumping it back on the site of origin is so expensive that is is largely confined to roadside cleanup projects. This cost restriction against chipping is fortunate from the point of view of tree seedling establishment and forage production, because the small chips suffocate small seedlings of trees, shrubs, and herbaceous plants. It is because of this mulching and obliterative characteristic that a deep ground cover of sawdust, wood chips, or bark chips is used as a means of weed control in park and urban landscaping. Incidentally, if finely divided or chipped wood is stirred into the soil, the carbon-nitrogen ratio becomes disadvantageous to plant production unless the condition is alleviated by adequate application of nitrogen fertilizer.

Mechanical crushing or compacting of certain diameters of thinning' slash has been studied in the pine forest type by Dell and Ward (1969). The roller-crusher known as the "Tomahawk" attachment for the blade of a D-6 crawler tractor was found to be effective in cutting and breaking slash up to 4 inches (10.15 cm) in diameter; and larger pieces, 6 to 8 inches (15.24 to 20.32 cm) in diameter, were skinned, delimbed, and compacted close to the ground. Although one pass of the tractor and its attachment over the slash sufficed for minimum fire control standards, a second **pass** provided improved access and better appearance. The quality of access provided would be important to big game and livestock, and the machine seems to have promise for meeting such a management objective. Exposure of mineral soil by the machine could mean some temporary reduction of vegetation; however, 'this initial restriction would likely be a very acceptable trade off to total loss of forage for several years under **3** feet (about 1 m) of untreated slash. Furthermore, where needed, ground cover vegetation could be rehabilitated by seeding measures.

Where slopes are too steep for crawler tractors to efficiently negotiate, machine treatment of slash would probably be impractical. On such sites fire hazard reduction and access for grazing animals might be improved by lopping limbs with lightweight powersaws, although such a minimal treatment would not alleviate the long-term obliteration and reduction of forage by coarse slash and cull logs. Leaving slash on steep slopes might have some value in checking possible soil erosion and thus maintaining forage productivity on these sites. Untreated slash on steep slopes would also provide some screening cover for wildlife, although a fuel break around the perimeter of untreated areas would probably be advisable.

ONGOING RESEARCH

In general, most of the ongoing research that deals with grazing animals in the forest environment is aimed at the broad objective of determining the effects of manipulating tree density (harvest, thinning, etc.) on habitat rather than on the more specific effects of debris accumulations and treatment of them. However, since accumulation of debris is an inevitable consequence of tree cutting, it is virtually impossible to study the influence of one on animal response and forage production without considering.the other. Even so, much of the information available on residue effects per se has been gained by chance rather than by design.

Although the authors are not fully aware of all ongoing research pertinent to the subject of this paper, two studies in their personal research programs bear on the issue. One, in the grand fir type of northeastern Oregon, is designed to compare plant succession and animal use on clearcuts with residues untreated, on clearcuts with residues broadcast burned, and on selectively cut areas with no treatment of residues. At one location deer and elk are the only grazing animals involved. At another, cattle also use the area, and responses are measured on contrasting aspects.

The other study was begun to determine optimum spacing for lodgepole pine in central Oregon. Residue resulting from the thinning of dense stands to achieve desired spacings were hand- and machine-piled off the treatment plots except for one on which slash was allowed to lie untreated. Understory vegetation and deer use are being measured as well as tree response. Data have not been processed at this writing, but some general observations are of interest. The plot on which the residues were untreated was essentially out of forage ,production immediately after thinning because the dense jumble of stems left it impenetrable. After 5 years, a rough estimate revealed that approximately one-half the area of this plot was accessible to deer, and deer droppings were observed in several of the more open portions.

SUMMARY AND CONCLUSIONS

Only modest generalizations can be derived from the meager literature concerning the influence of forest residues on habitat for grazing animals. Untreated heavy pieces of debris and large volumes of small-diameter residues obviously eliminate forage for many years. Cattle are slightly more restricted than deer and elk by presence of slash. Blockage of trails to water is critical. Patchy distribution of residues seems to be less of a deterrent than uniform distribution. Effects of untreated slash diminish with natural decay, but the rate at which this occurs in the various combinations of forest types and cutting systems has not been adequately described.

Burning has been the most widespread practice in residue reduction and is effective in improving access. It also affects plant succession, improving the species composition for grazing animals in some cases and damaging it for a time in others. The net effect varies with the existing vegetation and physiography of the site and with the type of burn--broadcast or pile. At some point, the burning influence on the site becomes subordinate to other factors that guide succession such as microclimate, moisture, and fertility. Identification of that particular point is probably not as important as following successional patterns after various treatments long enough to document the trends of preferred forage species in the various forest habitats. Much, but not all, successional research has been limited to changes occurring in the first 5 to 8 years after disturbance and to harvest systems that have been accepted as standard for a particular forest type; e.g., high-lead clearcut logging followed by broadcast slash burning in coastal Douglas-fir forests. Consequently, detailed successional patterns for the entire period of forest reestablishment, for other forest types, and for other harvest systems have not been worked out. Although several techniques for residue disposal other than burning have been tried, none have been studied for their effect on succession or animal use. Absence of any great increase in successional studies is probably in part a result of growing use of cultural or management practices which reduce reliance on natural recovery processes. Herbicides, reseeding, replanting, and fertilizers can, to a considerable extent, control timing, quality, and quantity of revegetation when values and financing permit such cultural operations.

NEEDED REVISIONS IN CURRENT PRACTICE

As one reviews the equipment which is available in recent years, it appears there are types of equipment and forest practices which would benefit access of grazing animals in slash covered areas. One item which could be used more in slash treatment without research or study is the lightweight model of the powered chain saw. This is an excellent tool for delimbing heavy branches and tops to get slash down off its "spider legs," and thus remove obstructions to large animals and also hasten slash decay by contact with the soil. The little saws should be particularly useful on terrain where tractor-mounted equipment for treating residues should not be allowed.

Planning and supervision of precommercial thinning projects can be improved without involving research. A definite effort should be made in thinning work and even in logging shows to prevent blockages of important livestock and game trails to streams and water developments, or the problem should be corrected as soon as possible after thinning and logging operations.

Yarding unutilized materials (YUM) is a practice that seems to have been suggested for esthetic reasons, yet it is important as a residue treatment in the interest of improved accessibility and forage production for grazing animals. The need for this practice is especially great in the coastal Douglas-fir areas and in the grand fir or mixed conifer type of the interior Northwest where heavy slash and cull logs are likely to cover 25 to 30 percent of a clearcut.

RESEARCH NEEDED

The habitat manager for wild and domestic grazing animals needs to know for each feasible residue treatment method the effect (1) on accessibility of forage area, water, and cover; and (2) on net change in production of forage and protective ground cover with and without rehabilitation measures following treatments. This information is needed for each major forest type and for each combination of silvicultural system and logging method.

Some of these studies could easily raise questions on tree regeneration. Hence, in addition to range, wildlife, and residue treatment scientists, a multi-discipline team working on some of these proposals should also include a silviculturist.

EQUIPMENT DEVELOPMENT

Some sort of machine treatment of logging or thinning slash, particularly in the forest types of the interior Northwest, seems to be indicated as a possible alternative to burning. All treatments seem to destroy some ground cover vegetation. Reducing this disturbance for burns may not be possible, but in the further refinement of machine-treatment devices, some way of reducing soil and plant disturbance should be considered. In lieu of this, some replacement of tree seedlings and reseeding of ground cover species should be planned.

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DECAY

Paul E. Aho

ABSTRACT

Forest residues from Zogging and catastrophes are deteriorated by associations of insects and micro-organisms. Insects are vectors, create infection courts, and provide for rapid spread of micro-organisms within residues. Many kinds of micro-organisms attack dead wood; however, Basidiomycete fungi--particularly **Polyporus abietinus, P. volvatus, Ganoderma applanatum, Lenzites saepiaria,** *and* **Fomes pinicola**--*cause the greatest amount of decay.*

The primary factors affecting deterioration of residues are moisture, temperature, and decay resistance of the wood. Soil type, slope aspect and percent, elevation, and degree of shading strongly influence temperature and moisture of residues. Tree species, age, and growth rate affect degree of resistance to decay. Management decisions, such as type of cutting operation and time of year that it is made, also influence decay rate of residues.

Alternative residue treatments are needed in excessively wet or dry sites, in recreation areas, or where fire hazard is high.

Keywords: Decomposition--decay, fungi.

INTRODUCTION

Residues, whether from natural catastrophes or man caused, create management problems in Pacific Northwest forests. Increased fire hazard, interference with regeneration of the site, and spread of insects and diseases to residual trees are only a few of these problems.

Natural catastrophes, such as fires, wind, snow and ice storms, and insect and disease epidemics, can cause large amounts of residues. However, salvage operations generally remove merchantable material as soon as possible to reduce further losses from insects and decay fungi. Residues remaining after salvage work are often similar to slash resulting from partial or clearcut logging operations.

Once merchantable material is removed, it is important to know as much as possible about the conditions affecting the deterioration rate of the remaining residues. It is important to know how residues should be treated to promote deterioration and decay. The purpose of this paper is to report what is known and what needs to be known about deterioration of forest residues in the Pacific Northwest.

CLIMATIC PATTERNS IN RELATION TO RESIDUE DECAY

Deterioration of forest residues is influenced by the macroclimate (mainly temperature and precipitation) of the geographic area where the residues are located. The climate of the Pacific Northwest is strongly affected by mountain masses which are barriers to both maritime and continental airmasses. Climatologically, this region can be divided into three areas; western Washington and coastal and northwestern Oregon, southwestern Oregon, and eastern Washington and Oregon. The climates of these areas can be characterized in general terms; however, it should be remembered that there is much variation within an area depending on elevation, slope, aspect, latitude, and other conditions.

Western Washington and coastal and northwestern Oregon have a maritime climate characterized by wet, mild winters with a long frost-free period and relatively cool, dry summers. During spring and winter, moisture within residues is sufficient for decay; however, temperatures are less than optimal. Summer and fall temperatures are near optimal, but moisture content is often too low.

In southwestern Oregon, summers are warm and winters are somewhat cool. Total precipitation during the year is low, especially during the summer when a drought period develops. In this area, winter temperatures and the hot dry summers retard decay of residues.

In eastern Oregon and Washington, compared to the other areas, total annual precipitation decreases, summers are hotter and drier, and winters colder. Summer temperatures and lack of precipitation are definitely a limiting factor in deterioration of forest residues, as are cold winter temperatures.

In general, summer temperatures are generally lower and moisture is higher on the west slopes of the Coast, Cascade, and Blue Mountain Ranges than on east slopes. Temperature decreases and moisture increases with elevation at a given latitude. At a given elevation, temperatures increase and moisture decreases from north to south. Northeast, north, and northwest slopes are generally cooler and moister than other aspects; and southeast, south, and southwest are hotter and drier. More detailed information concerning the climate of the Pacific Northwest can be found elsewhere (U.S. Weather Bureau 1960a, 1960b).

RESIDUE DETERIORATING ORGANISMS

Few studies have been made on deterioration of logging slash in the Pacific Northwest (Childs 1939, Roff and Eades 1959). Information from two slash decay studies made in other areas is pertinent to a discussion of this problem and will be drawn on extensively[1] (Wagener and Offord 1972). Deterioration of trees killed by wind (Boyce 1929, Buchanan and Englerth 1940, Childs and Clark 1953, Shea and Johnson 1962, Engelhardt 1957, Wickman 1965), fire (Kimmey apd Furniss 1943, Kimmey 1955), and insects (Boyce 1923, Wright and Wright 1954, 'Wright et al. 1956, Shea et al. 1962, Wright and Harvey 1967, Johnson et al. 1970) have been studied. Since 53 percent of logging residues are over 15 inches (38.1 cm) in diameter and 82 ercent are over 8 feet (2.4 m) long in western Washington and Oregon (Howard 19717, information from the above studies should be applicable to decay of slash.

Needles, twigs, and small branches are normally destroyed during slash burning; and if unburned, they are decayed by unidentified duff- and humus-inhabiting fungi (Childs 1939). Decay of litter and duff is discussed by Bollen (1974). Larger branches and logs are decayed mainly by higher fungi belonging to four families (Agaricaceae, Polyporaceae, Thelephoraceae, and Hydnaceae) in the class Basidiomycetes (Boyce 1961).

In the Pacific Northwest most wood-destroying fungi infecting slash appear to usually confine their activities to dead material (Childs 1939). However, identification of these fungi in the past was largely on the basis of presence of sporophores or visual examination of decayed wood instead of by cultural techniques. Identification, based on extensive cultural isolations and presence of sporophores, of fungi attacking lodgepole pine logging slash in an area in Alberta indicated that seven fungi were associated with most of the decay, and' four of these are important in living trees (see footnote 1).

The fungi in table 1 are presently recognized as. the important slash destroyers in Pacific Northwest tree species. Future studies may indicate others just as important and may also clarify the role of fungi causing heart rots in living trees in deterioration of residues. For instance, fungi causing decay in living trees may be important slash destroyers in old-growth forests but have relatively minor roles in young forests. The fungi in table 1 can be divided into two broad groups based on which wood components they are capable of utilizing.

Fungi causing white rots decompose all cell wall substances, usually attacking lignins first, then cellulose and other polysaccharides. Brown rot fungi degrade cellulose and associated pentosans but leave lignin virtually intact. The most important white rot fungi attacking residues of most tree species are *Polyporus abietinus*, P. *versicolor*, and *Ganoderma applanatum*. *Fomes pinicola* and *Lenzites saepiaria* are the major brown rot fungi.

Many fungi sporulate on slash; however, the presence of sporophores is not a reliable indication of either the fungi causing the greates't percentage of decay or the amount of decay present (Buchanan 1940). Most decay and fruiting by fungi attacking only the sapwood occur most commonly the first few years after residues are created (table 1). They are followed by fungi capable of degrading both sapwood and heartwood. After the sapwood is badly deteriorated, fungi that attack only heartwood become important. In the final stages of deterioration, several fungi are often simultaneously decaying residues.

1/ A.A. Loman. Deterioration by decay of lodgepole pine slash near Strachan, Alberta. Interim Technical Report. Canada Agriculture, Research Branch, Forest Biology Division, Forest Biology Laboratory, Calgary, Alberta. 22 p., 1959.

Table 1.--*Fungi presently recognized as the most important destroyers of slash from Pacific Northwest tree species listed in order of importance by type of rot and wood attacked*[1/]

Fungus and rot type	Douglas-fir	Western hemlock	Sitka spruce	Pacific silver fir	Western redcedar	Ponderosa pine	Lodgepole pine	White fir	Subalpine fir	White spruce	Sugar pine
White sap rots:											
Polyporus abietinus	+	+	+	+		+	+	+	+	+	+
Ganoderma applanatum	+	+	+	+	+			+			
P. versicolor	+	+	+	+	+						
Fomes annosus	+	+	+	+		+		+			
P. volvatus	+	+	+	+		+		+			+
Stereum sanguinolentum	+	+	+	+			+		+	+	
Amylostereum chailletii	+	+	+	+			+		+	+	
P. anceps						+					+
P. gigantea	+									+	
P. cuneatus					+						
Schizophyllum commune		+	+								
White heart rots:											
G. oregonense	+	+		+							
Armillaria mellea	+	+	+	+				+			
Poria cinerescens		+	+	+							
P. subacida		+	+	+							
Polyporus montanus		+	+	+							
Hymenochaete tabacina		+	+	+							
Peniophora incarnata		+	+	+							
Naematoloma sp.	+										
P. phlebioides	+						+				
F. putearius	+										
Pholiota adiposa								+			
Brown sap rots:											
Lenzites saepiaria	+	+	+	+		+	+		+	+	+
Coniophora puteana	+						+				
Brown heart rots:											
F. pinicola	+	+	+	+		+		+	+	+	+
Polyporus fibrillosus	+	+	+	+							
F. officinalis	+							+			+
Poria carbonica	+	+	+	+							
P. monticola	+	+	+	+							
Trametes serialis		+	+	+							+
P. xantha	+	+	+	+							
P. ferrea		+	+	+							
S. abietinum		+	+	+							
Trechispora brinkmanni		+	+	+			+				
F. cajanderi	+						+				
Polyporus sulfureus	+										

[1/] Sources include papers on slash decay and deterioration of dead trees from the Pacific Northwest, California, and western Canada (Boyce 1923, Boyce 1929, Buchanan 1940, Childs 1939, Kimmey 1955, Kimmey and Furniss 1943, Loman 1962, Roff and Eades 1959, Smith et al. 1969, Wagener and Offord 1972, and Wright et al. 1956).

Insects are intimately associated with these fungi as they serve as vectors and create infection courts (Mitchell and Sartwell 1974). The rate of deterioration of residues is therefore closely related to insect activity (Smith et al. 1969, Basham and Belyea 1960, Wright and Wright 1954). The general pattern of deterioration of forest residues begins with attacks by bark beetles and ambrosia beetles which are vectors of staining and sapwood destroying fungi. Staining fungi (often blue stains) are usually confined to the sapwood where they utilize the contents of parenchyma cells in wood rays but are not known to have enzymes capable of breaking down cell wall components (Liese 1970). Staining is followed by sapwood decay, or both processes may occur simultaneously since both groups of fungi are associated with the same beetles or use their entrance holes for infection courts. These fungi rapidly spread throughout the sapwood to the heartwood and some, especially *F. pinicola*, are also capable of decaying heartwood. Finally, wood borers that penetrate deep into logs may act as vectors of heartwood rotting fungi and create favorable conditions for rapid spread of decay.

It has long been known that successions and associations of wood-staining and decaying fungi deteriorate forest residues (Buchanan 1940). Evidence is now accumulating which suggests that associations and successions of additional micro-organisms, including bacteria, yeasts, and other lower classes of fungi,[2/] are also responsible for decay of wood (Shigo 1967). Numerous studies of micro-organisms associated with decays in living hardwoods and conifers have shown that bacteria and lower fungi are commonly associated with wood-destroying fungi in all stages of decay. Eighty-one fungi, including numerous lower fungi, have been isolated or observed fruiting on lodgepole pine slash (see footnote 1). The roles of lower fungi in the decay process are largely unknown.

Two groups of micro-organisms may have more important roles in deterioration of wood than is now realized. Some lower fungi, often referred to as "soft rot" fungi, are capable of degrading wood, usually to a lesser extent than wood-destroying Basidiomycetes. Large cavities between the tertiary cell wall and lignified middle lamella are characteristic of soft rot in coniferous wood. Although soft rot fungi do not cause extensive decay in a short time, they may nevertheless be important because they can degrade wood that is very wet or frequently dry, whereas the Basidiomycetes might not survive (Duncan 1960).

Bacteria have long been known to occur in discolored and decayed as well as in sound wood. Known to increase permeability of wood by attacking pit membranes, they are commonly found in sapwood parenchyma cells which contain an easily available source of carbohydrates. Some wood-inhabiting bacteria have enzymes capable of utilizing pectin, others can degrade cellulose, and some can even degrade lignin (Liese 1970). In addition, bacteria capable of fixing atmospheric nitrogen have been isolated from all types and stages of decay in living white fir trees (Seidler et al. 1972). A study of decaying American chestnut logs has demonstrated that nitrogen fixation takes place and nitrogen content increases as these logs decompose (Cornaby and Waide 1973). Since wood is especially low in nitrogen content, this could be a very significant factor in decay of wood and another piece of evidence to support the theory that decay is caused by associations or successions of micro-organisms.

2/ For simplification, "lower fungi" as used here and elsewhere in this paper includes species of fungi from the Phycomycetes, Ascomycetes, and imperfect fungi.

FACTORS AFFECTING DECAY RATE

Conditions affecting infection and subsequent development of insects and fungi will determine the rate of residue deterioration. Insects attacking residues are discussed by Mitchell and Sartwell (1974). In addition to a food base, decay fungi require adequate temperatures, moisture, and oxygen to grow. When these conditions are optimal, deterioration occurs at its maximum rate. Several physical and environmental factors including soil type, elevation, slope aspect and percent, and degree of shading significantly influence temperature, moisture, and oxygen contents of forest residues. Relationships are often complex and difficult to measure under natural conditions. Therefore, much information in the literature is observational and sometimes conflicting. However, there is a body of information concerning deterioration of residues that is consistent enough that broad generalizations can be made for most tree species.

Temperature and moisture are, the most important factors governing decay rate of forest residues. Except on very dry sites, temperatures may be the most critical factor affecting decay rate in forests in western Washington and northwestern Oregon (Childs and Clark 1953); however, Hubert (1920) indicated that moisture is the controlling factor in Northwest timber-sale areas as did Spaulding and Hansbrough (1944) in the Northeast.

According to studies made with wood rotting fungi on artificial media, most favorable temperatures for most fungi ranged from 25° to 30" C (Cartwright and Findley 1958). In another study, decay fungi were separated into three groups; those growing best at low (under 24" C) temperatures, at intermediate (25" to 32" C) temperatures, and at high (over 32" C) temperatures (Humphrey and Siggers 1933). This in part explains why some fungi are consistently found attacking residues under certain environmental conditions. For instance, in Alberta, Canada, the distribution of fungi in lodgepole pine slash piles is related to temperature differences within the piles (Loman 1962). *Lenzites saepiaria* is known to grow optimally at temperatures above 32° C. However, this fungus also causes significant amounts of decay at 10" C (Loman 1962). It is found decaying slash on top of piles where temperatures are highest (Loman 1962); on dry sites, it is one of the few fungi that can decay exposed case-hardened sapwood (Childs 1939). Because of its ability to cause appreciable decay over a broad temperature range, *L. saepiaria* may be the most important decay organism on dry sites. Less heat tolerant fungi are found on the middle and bottom of slash piles where temperatures are lower.

Most wood decay fungi cannot attack wood with less than 20-percent moisture content (ovendry weight), and minimum moisture contents between 27 and 33 percent are needed for significant amounts of decay to occur (Boyce 1961). Wood easily absorbs moisture from wet soil, sometimes to the extent that airspaces within wood are filled with water. Such saturated or waterlogged wood cannot decay, because oxygen necessary for respiration and growth of fungi is not available (Boyce 1961). For a given tree species, the moisture content at which decay is inhibited is related to wood density (specific gravity). As wood substance in a given volume of wood increases, airspace is reduced; thus, less moisture will reduce air content below levels necessary for fungal respiration (Boyce 1961). However, among tree species, wood density is not related to resistance to decay since chemical components of the wood are more important (Boyce 1961).

Soil type influences humidity around residues and moisture contents within, especially when in contact. Sandy and pumice soils are usually drier on the surface and may have less ground cover to provide shade. Residues in contact with these soils dry quickly and become casehardened, retarding decay (Spaulding and Hansbrough 1944). In contrast, clayey soils tend to retain moisture and have dense vegetation which often leads to waterlogging of forest residues and little or no decay. Fastest decay of residues is usually on loamy soils (Spaulding and Hansbrough 1944).

Elevation influences decay of residues in several ways. Precipitation, much in the form of snow, increases with elevation, the sun's rays have a stronger effect at higher elevations, and day and night temperatures are more extreme. Compaction of piled and scattered slash by snow at higher elevations results in greater contact between ground and slash. On wet sites, residues may become waterlogged and decay impeded; however, on most other sites, decay will be promoted by ground contact. In general, temperatures throughout the year at higher elevations are cooler than at lower elevations; thus, there are fewer days when temperatures are optimal for decay to occur. Where snow remains on the ground until early summer, both temperature and moisture conditions are unfavorable for decay of residues most of the year. On dry south and west slopes at higher elevations, the stronger effect of the sun promotes rapid drying of the soil surface and residues, resulting in casehardening of exposed wood.

Slope aspect exhibits a strong influence on moisture and temperature. Generally northwest, north, and northeast aspects are cooler and wetter than others. This effect may be modified by degree of slope. Steep slopes receive less direct solar insolation; thus the soil and residue surfaces are cooler and moister. However, steep slopes may be drier due to rapid runoff of surface precipitation and subsurface water. Soils are often thinner, rockier, and thus drier. In western Washington and northwestern Oregon, rate of slash deterioration was faster on north slopes (Childs 1939); on the other hand, fire-killed Douglas-fir in the same region deteriorated faster on southern exposures, except at higher elevations where burned timber became dry and casehardened on south-facing slopes (Kimmey and Furniss 1943). Burned trees felled within 10 years after a fire deteriorated at the same rate as standing burned trees (Kimmey and Furniss 1943).

Shading by vegetation influences moisture and temperature on dry and wet sites. West of the Cascades, slash on dry sites decays slowly, especially in clearcuts until vegetation covers the area, increasing moisture and decreasing temperatures to levels conducive to decay (Childs 1939). On wet sites, shading lowers temperature's and maintains moist conditions, which can cause waterlogging of residues (Kimmey and Furniss 1943).

TYPE OF RESIDUES IN RELATION TO DECAY

Natural resistance to decay has been noted among various tree genera and even among species within a given genus (Boyce 1961). In western Washington and northwestern Oregon, residues from western redcedar deteriorate slowest, followed by Douglas-fir, then Sitka spruce, and finally Pacific silver fir and western hemlock which deteriorate at about the same rate (Childs and

Clark 1953). In northern California, Douglas-fir residues decay slowest followed. by sugar pine, ponderosa pine, and white fir (Kimmey 1955).

Regardless of species, sapwood in old-growth dead trees generally decays faster than heartwood (Buchanan and Englerth 1940). With the exception of ponderosa pine (Kimmey 1955), sapwood of all species usually deteriorates at about the same rate. Small logs deteriorate faster than large logs and top logs faster than butt logs (Boyce 1923, Childs and Clark 1953, Wickman 1965). This can be partly attributed to the sapwood-heartwood ratio. Large logs and butt logs generally have narrower bands of sapwood than small or top logs (Buchanan and Englerth 1940). In addition, large and butt logs, especially from certain tree species such as Douglas-fir, have thicker bark which retards drying of the sapwood. High sapwood moisture content prevents decay. Small and top logs with thinner bark and greater surface-to-volume ratio dry faster, allowing decay to develop sooner (Childs and Clark 1953). However, on dry sites at higher elevations, decay of top logs is impeded because they become too dry (Kimmey and Furniss 1943). Beetle entrance and exit holes aid passage of moisture from sapwood to the air. Severe beetle attacks result in bark sloughing off and casehardening of exposed sapwood on dry sites. Dried small branches are particularly resistant to decay fungi (Spaulding 1929). However, in larger branches and logs, drying checks develop through which fungi can infect susceptible sapwood or heartwood below casehardened wood. These checks also facilitate passage of available moisture to heartwood of logs (see footnote 1). Sapwood in log bottoms touching the ground is often too wet to decay (Buchanan and Englerth 1940). Tops and sides of logs deteriorate faster because of ambrosia beetle attacks and checking which contribute to drying of sapwood.

Residues from old-growth trees decay slower than those from young-growth because of thicker bark, a thinner ring of sapwood, narrower growth rings, and more durable heartwood. Branches from old-growth trees have more heartwood and decay slower than branches from young trees. Logs from open-grown stands usually have wider growth rings and will decay faster than logs from trees grown in dense stands which have narrow growth rings (Kimmey 1955, Basham 1957).

INFLUENCE OF MANAGEMENT PRACTICES ON DECAY OF RESIDUES

Forest management practices, such as type of intermediate or harvest cut, time of year that residues are produced, and slash treatment, influence decay rate of residues. In general, residues in clearcuts deteriorate slower than those in partial harvest cuts or in thinned young stands. In the summer, because of greater amounts of sunlight, slight rainfall, and low relative humidities, residues in clearcuts may become too dry to decay. Tests of wood samples from branches and logs in clearcuts indicated that sufficient moisture for decay was present only in inner sapwood and heartwood of logs exposed to full sunlight, in outer sapwood of logs with thick bark and under shade, and in branches in contact with at least partially shaded soil (Childs 1939). Nearly a quarter of the bark on cull logs less than 2 feet (61 cm) in diameter and on unmerchantable tops is ripped off during logging. The exposed sapwood often becomes too dry to decay or is sterilized by solar heat (Childs 1939). The rate of decay may be slowed by slash burning which can double the amount of bark removed (Childs 1939). Drying is more severe in thin-barked species, such as spruce and western hemlock. Sapwood moisture content is not high enough to ,promote decay even in the larger spruce and hemlock logs which might have thicker bark (Childs 1939). In general, residues in contact with the ground+decay faster than suspended residues. Branches that are not broken off during logging remain sound for many years; however, branches in contact with the ground usually decay within 10 years after logging (Childs 1939). Checking caused by shrinkage appears to be important in deterioration of slash in hot, dry sites such as in clearcuts (Childs 1939, Wagener and Offord 1972; see also footnote 1). This is especially true for suspended slash in clearcut areas (see footnote 1). Checks cause twigs and branches to break into smaller pieces, are infection sites for fungi, and allow passage of moisture to the interior of larger branches and logs.

Generally, residues created by partial harvest cuts and thinnings decay considerably faster than residues in clearcuts. Prolonged exposure to summer sunlight is considerably reduced in the former, temperatures are usually slightly lower, and relative humidities are slightly higher. In addition, there is often more ground cover to furnish shading which further modifies the microclimate. Slash created by thinning generally decays at a faster rate than under partial harvest cuts because thinnings are generally made in young stands. Young trees deteriorate much faster than old trees for the reasons already given.

There are instances when decay proceeds faster in residues in clearcuts than in partial cuts. In Alberta, Canada, lodgepole pine residues deteriorated fastest in clearcuts, presumably because the frequent summer rains wetted residues, whereas rainfall was intercepted by overstory trees in partial cuts (see footnote 1). The increased moisture reaching slash in clearcuts easily penetrates to the interior of residues through checks and is utilized by decay fungi.

Whether residues produced at one time of the year decay faster than those created at another time is problematical. In northwestern Oregon and western Washington, slash from Douglas-fir, western hemlock, Sitka spruce, Pacific silver fir, and western redcedar, decays faster when felled in spring or summer (Childs 1939). Insect-killed balsam firs in Ontario that died in summer deteriorated more rapidly than those that died during winter (Basham and Belyea 1960). Conversely, ponderosa pine logs in eastern Oregon cut in spring degrade slower than those cut in winter (Boyce 1923), and decay rate of second-growth Douglas-fir trees in British Columbia was faster for autumn and winter trees than for those cut in spring and summer (Smith et al. 1969). Infection and penetration of ***Fomes pinicola*** in Douglas-fir logs were closely associated with ambrosia beetle attacks which in British Columbia prefer logs created in autumn and winter (Smith et al. 1969). Deterioration rate of residues may, therefore, be closely associated with seasonal attacks by insects, particularly beetles.

Slash treatment influences the rate at which residues deteriorate. Several slash disposal methods have been used including piling and burning, broadcast burning, piling or windrowing, and lopping and scattering. Each of these methods has its advantages and disadvantages. Burning has been widely used on public forests in the Pacific Northwest and is considered the best method in terms of forest sanitation (Boyce 1961). Needles, twigs, and all but the largest branches are eliminated by burning in clearcuts in western Washington and northwestern Oregon, thus reducing fire hazard drastically (Childs 1939). In unburned clearcuts, needles and twigs deteriorate in 10 or 12 years. Decay rate of larger branches and logs with durable heartwood is impeded slightly by burning. This can be partially attributed to surface charring. Charred wood seems to be highly resistant to decay and protects sound wood, which it surrounds, from fungal infection. Eventually checks develop in charred surfaces through which decay fungi attack the wood beneath (Hunt and Garratt 1953). Other advantages and disadvantages of slash burning are discussed by Bollen (1974).

Under most conditions, any slash treatment system that puts residues in contact with the ground will hasten decay. Therefore, lopped and scattered slash usually deteriorates faster than suspended, piled, or windrowed residues. However, on very dry sites, compact piles will deteriorate faster than scattered or loosely piled slash because moisture loss is retarded. On very wet sites, placing slash on the ground by lopping may result in waterlogging and decreased decay rates.

Mechanical treatment, including chipping or crushing of residues and spreading them over the soil or burying them in it, offers the fastest method of eliminating forest residues in most situations. Techniques, advantages, and problems associated with these slash disposal methods are discussed in detail by Bollen (1974). A crushing technique, apparently used successfully in lodgepole pine clearcuts in the Rocky Mountain region, uses a Mardin chopper.[3/] The chopper, a large drum with blades and pulled by a tractor, puts slash on or under the ground in relatively small pieces. The Mardin brushcutter was tested in a ponderosa pine thinning study in the Deschutes National Forest, Oregon, and was found to be limited to slopes less than 35 percent steep (Dell and Ward 1969). A "Tomahawk" crusher, mounted on a D-6 tractor, was effective in reducing fire hazard in thinning slash, was economical, and did not damage leave trees.

Chipping or crushing of residues and spreading them over the soi'l or burying them in it should not be done on wet sites, such as heavy wet, clayey soils in the Coast Ranges or northwestern Oregon or on very moist north slopes at higher elevations, and where large accumulations of duff are already present. Other disposal techniques should be used under these situations.

Acceleration of slash decay by treatments with various amendments and chemicals has resulted in little or no success. Applications of nutrients and mycelium of wood decay fungi to lodgepole pine slash was at best inconclusive in hastening deterioration (see footnote 1). The experiment might have been successful had the amendments been applied to older instead of fresh slash. Shrinkage cracks in older slash would probably have allowed penetration of inoculum resulting in deep-seated infections and increased decay.

Another chemical compound, Reynolds No Fire #CA15, has been reputed to hasten the decomposition of slash. The manufacturer of this dark oily liquid claims that it causes lignins and resins to be released prematurely, thus cresting a more favorable environment for development of wood-decay fungi (Hendee et al. 1966). First year results of field tests of this compound had indicated a difference in decay between treated and untreated slash. Laboratory studies failed to substantiate the results of the field tests. There were no differences in hyphal activity of *Ganoderma applanatum* between treated and untreated wood samples. Field tests of this chemical have been continued, however, because of the favorable results obtained initially (Hendee et al. 1966).

3/ Personal communication with T.E. Hinds, Plant Pathologist, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Application of mixtures of 2,4-D and 2,4,5-T in oil with fertilizer has been reported to accelerate deterioration of stumps (Curtis 1957). Mixtures of the amine forms of 2,4-D and 2,4,5-T were applied to pieces of Douglas-fir sapwood and branch wood with intact bark.[4/] The test material was placed under timber stands on north-facing slopes in the Estacada Ranger District in the Mount Hood National Forest. No differences were noted in deterioration rate of treated over untreated test pieces after 2 years of field exposure. Other chemical compounds or amendments were also tested during this study in attempts to accelerate decay of wood under field conditions. Various forms of nitrogen, including ammonium phosphate, urea, and asparagine, were applied to test pieces of wood as previously described for mixtures of herbicides. Unlike laboratory studies in which addition of these substances to wood blocks increased decay rate over untreated wood (Findlay 1934, Hungate 1940, Schmitz and Kaufert 1936), deterioration rate by decay fungi was not noticably increased over controls after 2 years under field conditions. Similarly, application of liquid plastic, a compound that reduces moisture loss from treated wood, failed to promote more rapid decay over. untreated controls. Any differences in decay rate observed after treatment with the herbicides, various nitrogen sources, or the moisture retardant were attributed to site differences and not to the treatments. It was concluded from this study that none of these treatments were effective.

RESEARCH IN PROGRESS

Little research is in progress to determine methods for promoting deterioration of forest residues from man's activities or from catastrophes. A study is being made of deterioration of a standard size piece of residue under various environmental conditions./ Several scientists are studying decays of living trees with special emphasis on the decay process./ Information from these studies will be useful and applicable to deterioration of forest residues.

NEEDED RESEARCH

Since deterioration of forest residues is caused mainly by close associations of insects and micro-organisms, learning as much as possible about these relatio'nships is important. This knowledge would be useful not only for hastening deterioration rates of residues but also for protecting residual trees in

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4/ Unpublished data from a study on accelerating natural decay carried out by Frank Ward, Pacif c Northwest Forest and Range Experiment Station, Portland, Oregon.

5/ This study s under the direction of Dr. Charles Driver at the University of Washington, Seatt e, Washington.

6/ Dr. Alex Sh go at the Northeastern Forest Experiment Station, Durham, New Hampshire, leads a pioneer project studying decays and discolorations of northern hardwoods. Paul E. Aho at the Forestry Sciences Laboratory, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon, is studying decays of western conifers.

the vicinity of slash. Answers to the following questions would provide information necessary for timing logging operations to take maximum advantage of insect activity. What makes a log appealing to ambrosia, bark, and boring beetles? Is there a population level of various beetles that will promote rapid deterioration of residues and yet not be a hazard to residual living trees? Can this hypothetical population level be controlled by biological or chemical means? And finally, what kinds of micro-organisms are associated with beetles attacking residues at various times of the year?

Studies of the various micro-organisms associated with decay would be very important. Cultural studies, utilizing various types of growth media, should be undertaken to determine which micro-organisms are associated with decays of different tree species. Laboratory studies should then be made to learn the roles of the important micro-organisms. Since Basidiomycete fungi cause the greatest amounts of decay, it would be important to find out how decay by these fungi can be stimulated. We need to know which of these fungi are capable of producing rapid decay in hot, dry residues and in cool, wet wood, and then, to learn how to germinate their spores and inoculate residues under field conditions.

Decay rate by fungi has been increased in laboratory studies by addition of various forms of nitrogen (Findlay 1934, Schmitz and Kaufert 1936, Hungate 1940). Although nitrogen-fixing bacteria have been isolated from decay in living trees and nitrogen-fixation occurs in decaying chestnut logs, we still do not know if nitrogen fixed by bacteria is available and used by fungi causing decay. We need to know whether nitrogen-fixing bacteria are associated with decays of residues and if not, whether deterioration rate can be significantly increased by addition of these bacteria.

Of the other micro-organisms associated with decays, it would be necessary to learn how important soft rot fungi are in deterioration of residues in dry and wet sites. These fungi may be quite valuable in decay of buried residues.

EQUIPMENT SUGGESTIONS

Development of heavy equipment for chipping or crushing large diameter logs under severe topographic conditions should receive high priority. The chipper should have the capability of either blowing chips evenly over the soil surface or incorporating them a few inches under the surface. It would also be necessary to learn how much and what type of fertilizer to use in various situations.

CONCLUSIONS AND DISCUSSION

Deterioration of forest residues even under the most favorable conditions is a long-term process. For instance, in clearcuts in the Douglas-fir type, only 70 percent of small (less than 1 inch (2.5 cm)) branch volume and 60 percent of large (larger than 1 inch (2.5 cm)) branch volume was decayed 16 to 20 years after logging (Childs 1939). Average volume of decayed sapwood and heartwood in tops and small logs (less than 2 feet (61 cm) in diameter) was 90 percent and 20 percent, respectively, in unburned clearcuts and 78 and 43 percent in burned clearcuts. Heartwood in larger logs remains sound for decades. Since a high proportion of logging slash in Pacific Northwest forests is still of large diameter and from old-growth trees, some form of slash disposal will be necessary to eliminate this problem. On most forest lands managed mainly for timber production, current methods may be sufficient. Since deterioration is caused mainly by associations of insects and micro-organisms, information from studies of these interactions would be useful for developing techniques to hasten deterioration rate. Determining the roles of various micro-organisms in the decay process, especially those of nitrogen-fixing bacteria and soft rot fungi, would be important.

Other methods to eliminate slash will be necessary on forest lands where for special reasons natural deterioration would take too long. Most promising techniques to speed up deterioration include chipping and crushing residues. Ground contact or even burial will in most situations result in faster deterioration. Development of heavy equipment capable of working on severe topographical sites will be necessary.

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INSECTS AND OTHER ARTHROPODS

Russel G. Mitchell and Charles Sartwell

ABSTRACT

Forest residues are utilized by many insects--pests as well as beneficia2 species. The most serious pests are bark beetles. Prominent among these is the Douglas-fir beetle, whose outbreaks are mainly associated with natura2 debris created by wind and ice storms. Other pests, such as the balsam woolly aphid, hemlock bark maggot, and a couple of weevils, have important but indirect associations with forest residues.

Many natural enemies of pest insects also live in residue materials. But perhaps more beneficial to forest productivity are the species involved in mineral cycling--those that fragment debris and litter.

Conclusions are that certain residues in Douglas-fir and ponderosa pine often create serious pest problems that should be considered in residue management programs. But the beneficia2 aspects of insects associated with residues may have more significance to man's objectives in the Zong run. Much 'research is needed to evaluate the significance of the various factors invotved.

Keywords: Insect damage--population buildup; residue deterioration--beneficial arthropods.

INTRODUCTION

Natural and manmade forest residues are shelter, food, and reproductive sites for a great variety of insects. A single windthrown tree may provide habitat for hundreds of species before it is thoroughly decomposed. That includes some well-known pests, notably several bark beetles. But most of the insects are decidedly beneficial to mankind, among them natural enemies of pests and fragmenters of forest litter. Populations of both pest and beneficial insects can be drastically affected by residue manipulation and disposal practices. Accordingly, insect interactions with forest residues must be considered in residue management.

With a few exceptions, forest residues are sources or causes of insect pest problems only for a year or two after the debris appears. Within the critical period, there is some controversy about whether these materials are entomologically hazardous because they may attract large numbers of tree-killing insects into a small area, or because the residue is an especially favorable breeding medium for some pest species. Often, both factors appear to apply, but their importance varies with each situation. Thus, for pest control, timing of residue treatment is usually more important than how the residue is treated.

However, the probability of a pest problem stemming from residues is often rather small, so the situation becomes one of considering beneficial insect species. This, in turn, places the emphasis on how the residue is treated rather than when it is treated. Generally, the more comprehensive disposal practices, such as broadcast burning of slash, act unselectively upon both pests and their natural enemies. Also, many kinds of residue treatments will likely reduce abundance of insects active in the natural deterioration of forest debris and litter. The long-term consequences of these effects upon stand stability and site productivity are not well known. But there is enough research to suggest beneficial insects should be considered.

Aspects of the residue relationships of both pest and beneficial insects are discussed in this paper. Since the literature background is often meager, much of the discussion stems from empirical evidence accumulated by foresters and entomologists over many years. The discussions apply only to forest conditions in Oregon and Washington. Different factors may govern these relations elsewhere.

PEST INSECTS

Bark beetles (family Scolytidae) are the major residue-associated pests in Oregon and Washington. Many kinds of wood-boring beetles (families Cerambycidae, Buprestidae, Platypodidae, and Scolytidae) attack and breed in residue materials, but only a few species attack living trees. Two weevils (family Curculionidae) have been recorded damaging seedlings and saplings in some residue situations. An aphid has been found indirectly related with Pacific silver fir (*Abies amabilis* (Dougl.) Forbes) slash and a fly with western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) slash.

Most pest problems generated by residues have been associated with Douglas-fir (***Pseudotsuga menziesii*** (Mirb.) Franco) and pine (***Pinus*** spp.). Residues from cedar (*Thuja plicata* Donn), hemlock (*Tsuga* spp.), true firs (***Abies*** spp.), spruce (*Picea* spp.), and larch (*Larix* spp.) have presented few or no pest problems.

BARK BEETLES

The Douglas-fir beetle, ***Dendroctonus pseudotsugae*** Hopkins, is unquestionably the foremost pest of mature Pacific Northwest forests. This reputation is gained mostly in areas west of the Cascade Range, where its tree-killing outbreaks on Douglas-fir are largely associated with windthrow, ice breakage, and wildfire. Two other bark beetles, ***Pseudohylesinus nebulosus*** (LeConte) and *Scolytus* ***unispinosus*** LeConte, commonly attack and breed in Douglas-fir residues. Occasionally these insects kill sapling and pole-size trees, but generally their role in removing suppressed and other weakened trees can be considered beneficial.

The correlation between Douglas-fir beetle outbreaks with trees damaged by winter storms and fire is well known in the coastal forests of Oregon and Washington. Windstorms, for example, in the winters of 1949-50 and 1950-51 blew down some 10 billion board feet of sawtimber in the Douglas-fir subregion (fig. 1). Then, in the 3 years following, another 3 billion board feet of standing timber were killed by beetles (Wright and Lauterbach 1958). Furniss (1941) noted that beetles associated with fire-scorched trees in the Tillamook Burn of 1933 killed some 200 million board feet of green timber.

Figure 1.--Windthrown Douglas-fir often attracts the Douglas-fir beetle in such great numbers that the adjacent green trees are attacked at the same time.

Most entomologists have long regarded the relationship between residues and tree killing as direct--beetles build up large populations in residues the first year and attack living trees the next season (Hopping 1915, Swaine 1918, Miller 1928, Bedard 1950, Keen 1952, Lejeune et al. 1961, Johnson et al. 1961, Furniss and Orr 1970). This is the rationale for the recommendation that tree killing can be prevented by removing infested materials before the beetle progeny emerge.

Recently, however, there has been a revival of the perspective of Graham (1922) and Craighead et al. (1927), who held that the buildup idea was too simplistic and often inconsistent with patterns observed in the woods. They contended that the heaviest tree mortality was generally due to effects of the slash in attracting beetles from surrounding stands and concentrating them in a small area where they can do greater damage than if widely dispersed. In keeping with this viewpoint are the observations of Johnson and Pettinger (1961) and Johnson and Belluschi (1969) that, when Douglas-fir beetle outbreaks develop, many standing trees are killed during the time nearby residues are under attack.

Research has shown that the attack pattern of the Douglas-fir beetle (and most other scolytids) involves two attractants. First, volatile plant terpenes attract a few pioneer beetles to the down or weakened trees (McMullen and Atkins 1961). Then, as the beetles bore into the bark, a powerful chemical attractant is generated which invites a mass influx of beetles to the tree (McMullen and Atkins 1962, Rudinsky 1966). If the beetle population in the woods is large, the original attractive source will not accommodate all the beetles drawn to the area. Adjacent green trees within 35 feet (10.7 m) will then be attacked (Johnson and Belluschi 1969), establishing new attractant centers which draw even more beetles to the area. Thus the group of infested and killed trees gradually expands outward throughout the flight period (fig. 2). Drought conditions, as occurred in the early 1950's, accelerate this pattern because the green trees are less able to reject attack when under stress.

Johnson and Belluschi (1969) concluded from their research that the beetles will congregate and kill trees when beetle populations are large and attractive brood material scarce. But when the reverse is true, all the beetles will be absorbed by the residue and few trees will be killed. After the Columbus Day storm of 1962, for example, an outbreak failed to materialize right away, even though the conditions seemed right (Orr 1963). In that particular instance, the preferred windthrown trees absorbed all the available beetles and none were left to attack green trees.

When this happens, foresters have a whole year to salvage trees before killing occurs. But, although estimates are annually available on the number of storm-damaged and fire-killed trees in the woods, the size of the beetle population waiting to attack this material is rarely known beyond a crude guess.

Thus far, although Douglas-fir beetle has occasionally caused postlogging mortality in interior forests, it has not caused serious damage in recently logged old-growth stands in western Oregon and Washington. Most slash accumulates in clearcuts, away from residual timber. Thus, its attractive nature is generally unimportant, except on the stand edge where a few trees are occasionally killed. Years ago, when many cull logs were often left after a harvest cut, slash probably contributed to the maintenance of large beetle populations in an area. However, utilization standards are now such that logging slash offers few good breeding sites for Douglas-fir beetle.

However, Johnson and Belluschi (1969) have sounded a warning for the future, when intermediate and selective cuttings of Douglas-fir will probably be more common. In such situations, down logs are generally well shaded and thus subject to attack for a long time. Also, they are usually close to green trees, which then are vulnerable to attack by Douglas-fir beetles. This hazard can be greatly reduced if logs felled during the beetle flight season of late April through August are removed from the woods as they are cut. This is particularly essential in years when large populations of beetles are expected.

Figure 2.--Douglas-fir group killing by the Douglas-fir beetle. Typically, beetles are drawn to an area by storm or fire-damaged trees with some spillover to green trees. Each attacked green tree then sets up a new attraction center which draws in more beetles and gradually expands the area of the group killing.

Spruce beetle, *Dendroctonus rufipennis* (Kirby),[1/] is extremely destructive to spruce forests in interior regions of western North America. Its major outbreaks generally have been associated with blowdown; and severe local infestations are frequently connected with logging residues, particularly cull logs (Massey and Wygant 1954, Schmid and Beckwith 1972). Tree killing has occurred locally in Engelmann spruce (*Picea engelmannii* Parry) stands of the Cascade Range and Blue Mountains, but regionally this damage has been modest because abundance of this tree species is limited (Orr 1963).

D. rufipennis also breeds readily in Sitka spruce (*P. sitchensis* (Bong.) Carr.) windthrows and logging slash. Moderate killing of Sitka spruce occurred during the mid-1940's on Kosciusko Island, Alaska, and in the early 1960's near

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1/ Among several synonyms are Engelmann spruce beetle, *D. engelmanni* Hopkins, and spruce beetle, *D. obesus* (Mannerheim).

Prince Rupert, British Columbia. Chamberlin (1958) mentions a small outbreak adjacent to blowdown on the Olympic Peninsula in 1933, but otherwise there is little evidence of this beetle being a pest in spruce stands along the Oregon and Washington coasts.

The most important insect enemy of mature ponderosa pine (*Pinus ponderosa* Laws.) is western pine beetle, *Dendroctonus brevieomis* LeConte, which is abundantly attracted to logging slash, windthrow, and fire-injured trees. Generally, there is little population increase in slash (Patterson 1927, Beal 1935). Tree killing in recently logged stands occurs primarily while the slash is under attack rather than during the time of new adult emergence (Craighead et al. 1927). Hence, disposal or treatment of slash is best done before it is attacked. However, slash-associated damage by this insect has been rather minor during recent years.

Western pine beetle apparently reproduces well in windthrown pine, as tree killing in the vicinity generally has increased for a season or two following blowdown (Miller and Keen 1960). Thus, salvage logging of currently infested windthrows can help prevent damage to the residual stand. Removal of fallen trees before they are attacked (as was done with most of the May 1971 blowdown in eastern Oregon) is even more effective.

Controlled burning of understory vegetation can generally be carried out without serious threat of subsequent damage by *D. brevicomis*, provided intended crop trees are not severely defoliated or injured by the fire. On the other hand, beetle-caused tree killing after a wildfire is often catastrophic. Trees most often attacked are those having lost more than 50 percent of their foliage in the fire (Miller and Patterson 1927, Salman 1934). Most tree killing seems the result of beetles aggregating within an area, rather than from population buildup by breeding (Miller and Keen 1960). Nevertheless, postfire tree killing usually continues at an epidemic level for 2 or 3 years. Thus, salvage removal of currently infested trees can reduce the beetle population and the probability of subsequent damage.

Mountain pine 'beetle, *Dendroctonus ponderosae* Hopkins, attacks several pine species. It breeds poorly in logging slash and fire-injured trees. Although it causes severe killing in dense pole stands of ponderosa pine (Sartwell 1971b), this insect rarely attacks the slash when such stands are thinned. There is some evidence that *D. ponderosae* populations can increase in windthrown trees, especially western white pine (*Pinus monticola* Dougl.); but overall, mountain pine beetle seldom causes a residue-associated pest problem.

Pine engraver, *Ips pini* (Say), is the principal pest associated with residues in the pine subregion, where about 100,000 acres (40,470 ha) of ponderosa pine sapling and pole stands are thinned annually. The thinning slash, which is generally left where felled, is not particularly good breeding material for *Ips pini* (Sartwell 1971a).[2/] Nevertheless, most of the slash is densely attacked by

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[2/] A comprehensive report about *Ips pini* brood production in ponderosa pine thinning slash is being prepared by Charles Sartwell, Pacific Northwest Forest and Range Experiment Station.

the beetle (Sartwell 1970). This aggregation of many attacking beetles in proximity to the intended crop trees occurs in the first spring or summer after a thinning; i.e., when the trees are suffering from the twin problems of recent severe competition with other trees and the shock of sudden exposure to full sunlight. Even so, ordinarily there is little damage to the residual stand; but when the situation is compounded by drought, spectacular tree killing may occur (Dolph 1971) (fig. 3).

Buckhorn[3] revealed that slash-associated tree killing by *Ips pini* occurs predominantly where slash was deposited during spring and summer. Thus, perhaps the best approach to minimizing damage is to schedule thinnings mostly in the fall and winter. Potentially, attractant chemicals might be used to lure attacking beetles to traps (Lanier et al. 1972), or repellants could be released to inhibit beetle migration into recently thinned stands. However, much research remains to be done with *Ips pini* pheromones.

Figure 3.--Pine engraver kill in a precommercially thinned stand of ponderosa pine.

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[3] W.J. Buckhorn. Preliminary report on the relation of logging operations to outbreaks of *Ips oregoni* in ponderosa pine forests. Unpublished report on file at Pacific Northwest forest and Range Experiment Station, Portland, Oregon, July 8, 1942.

Measures to suppress beetle populations developing in thinning residues could lead to reduced tree killing. However, these will minimize damage only if applied comprehensively on a regular basis. Sporadic, piecemeal treatments of infested slash will have little effect, because they will not accomplish a general lowering of the attacking beetle population in an area. Too, the probability of *Ips pini* damage to residual stands is seldom high enough to be the sole justification for sizable slash treatment costs. Hence, thinning with chemicals instead of by saw has considerable promise toward reducing the pest problem, because *Ips pini* brood production generally is very poor in silvicide-treated trees (Newton and Holt 1971).

Some slash treatments for decreasing the hazard of wildfire could also reduce developing beetle populations if applied earlier than is now done. Slash deposited in the fall and winter would have to be treated before the following July, and spring and summer slash by early September, i.e., generally while the needles of felled trees are still green. Infested slash piled and covered with black plastic produces very few new beetles (Buffam and Lucht 1968). Chipping is probably the best of available mechanical disposal methods. Crushing and mashing of thinning slash might reduce its suitability as breedina material for beetles, if the machine used efficiently breaks up fresh slash. However, this is merely a guess because effects of breaking up infested slash on *Ips pini* brood production have not been studied.

As to burying of infested residues, Miller and Keen (1960) report that most new adults of western pine beetle emerged and worked their way up through the soil from materials buried to a depth of 14 inches (35.6 cm). Perhaps much deeper burying would negatively affect brood emergence. However, extreme care would have to be taken in excavation, because injury to roots of surrounding trees would likely result in their being killed by other beetles.

Residues infested with western pine beetle have been effectively burned in pits and piles (Miller and Keen 1960). These burning techniques might be more difficult to use with *Ips pini*, because most new beetles leave the slash in early fall and overwinter in the duff. Broadcast burning has limited potential for reducing pine engraver populations, because it seldom can be done while beetles are still in the slash. If anything, fire injury to the cambium and foliage of intended crop trees would tend to increase damage by this insect.

Overall, however, residue treatments to minimize *Ips pini* damage would be most effective if applied before the thinning slash is attacked. This approach is probably best suited to high risk situations, such as recreational areas, or where severely stagnated stands are thinned in the spring or summer. Generally, this would mean treating the slash immediately after the thinning, because during warm weather, it is usually attacked within 2 to 3 weeks after felling. Chipping unattacked slash, removing it entirely from recently thinned areas, or piling it in large stand openings would prevent the aggregation of many attacking beetles in proximity to residual trees.

WOOD BORERS

Many wood-boring insects can seriously reduce the utilization possibilities for residues. However, in Oregon and Washington, only a few species cause appreciable killing of standing trees.

The most abundant insect breeding in Douglass-fir slash, as well as western hemlock, is the flatheaded fir borer (*Melanophila drummondi* (Kirby)). This relationship has posed no serious problems to date, but the beetle has a reputation of occasionally attacking and killing apparently healthy trees (Keen 1952). Possibly under the right conditions, such as extreme drought, slash-generated populations of the flatheaded borer could initiate some killing of adjacent green timber.

?he western cedar borer, *Trachykele blondeli* Marseul, attacks living western redcedar, tunneling in the heartwood and reducing merchantability. Damage by this beetle seems to increase after logging. The cause for this increase in damage is speculated to stem from a concentration of the normal beetle population on fewer trees, not because of buildup in slash or a mass of attraction of beetles. Because presence of this insect in residues is difficult to detect except by dissection, Doane et al. (1936) suggest immediate disposal of all fresh logging residues.

WEEVILS

A weevil (*Steremius carinatus* Boh.) commonly found in Oregon and Washington has been observed killing planted Douglas-fir and natural Sitka spruce in British Columbia clearcuts (Lejeune 1962). Larvae of the weevil breed in freshly cut stumps, and the omniverous adults feed on planted trees when they emerqe. Damage symptoms are similar to the feeding done by mice at the base of the stem. In the one instance (on Vancouver Island) where the weevil's pest status was recorded, some 40 percent of the planted Douglas-fir stock was killed or damaged. Reports indicate that most damage occurs in areas that were logged, burned, and planted within a **2-** or 3-year period. Much better information is needed on regeneration survival in Oregon and Washington to determine if *Steremius* is a pest here too.

A tiny weevil, *Magdalis* sp. probably *gentilis* LeConte, has demonstrated an interesting affinity for defoliating residual lodgepole pine (*Pinus eontorta* Dougl.) in newly thinned stands. The weevils do not seem to feed or breed in the slash, so the nature of their relationship with slash 's unknown. Heavy defoliation by feeding adults has been observed in Oregon?) and Montana (Fellin and Schmidt 1966). Fellin (1973) observed that the weevils attacked the trees only when the slash was fresh and mostly in stands thinned before late July. So far, defoliation has not been great enough to cause significant damage.

BALSAM WOOLLY APHID

An introduced pest from Europe, the balsam woolly aphid (*Adelges* ***piceae*** (Ratzeburg)), is related indirectly with logging slash in some of the lower elevation Pacific silver fir stands in the Coast and Cascade Ranges. The aphid attacks several true fir species but is particularly serious in Pacific silver fir stands below 3,000-foot (914-m) elevation (Mitchell 1966). There, the shade tolerant true fir has moved downslope to replace Douglas-fir, the dominant seral species. When these stands are logged, residual silver fir remain but no Douglas-fir. Because advanced silver fir reproduction is abundant, the trend has been to leave slash untreated for fear of destroying

4/ Private communication with Robert Dolph, Insect and Disease Control Branch, U.S. Forest Service, Region 6, Portland, Oregon.

the regeneration already present. The aphid then attacks the newly released silver fir and soon reduces the area to a brushfield (Johnson and Zingg 1968). Douglas-fir fails to regenerate because it lacks both a seed source and mineral soil for a seed bed.

The only solution to this problem has been to remove all residual 'silver fir and return the site to an earlier state of succession. Any treatment that eliminates the silver fir and provides mineral. soil for repopulating the site with Douglas-fir would be .effective. Broadcast burning has been successful and is the only system in use.

HEMLOCK BARK MAGGOT

The hemlock bark maggot (*Cheilosia alaskensis* Hunter) is another insect pest whose severity of attack is indirectly related to slash. Attacks by the fly on western hemlock produce a pitchy wound in the inner bark of the main stem; this defect is called black check or black streak in finished lumber (Moeck 1968). The connection between the bark maggot and slash arises because the fly must have entrance into the inner bark in order to attack. For this, it depends heavily on two bark beetles, *Pseudohylesinus tsugae* and *P. grandis.* These insects breed in slash and stumps but must feed as new adults in the inner bark of living hemlocks before the beetles can mature. Their small maturation feeding holes provide the entry to the inner bark needed by the bark maggot.

McGhehey[5/] found that precommercial thinning in young, coastal hemlock stands caused a significant increase in the maturation feeding attacks on residual trees by the two *Pseudohylesinus* bark beetles. This, in turn, greatly increased the incidence of attack by the hemlock bark maggot. Indications were that the increased maturation feeding was due to a larger beetle population in the area. When stands were thinned chemically with cacodylic acid, breeding beetle populations were much reduced over conventional thinning techniques and so we're the number of maturation feeding holes in residual trees.

BENEFICIAL INSECTS

Residue treatments may affect beneficial insects as well as pests. In some cases, certain kinds of residues might be purposely left untreated to conserve insect parasites and predators of pests (Berryman 1967). Slash also provides a good habitat for some insectivorous birds and mammals (Dimock 1974). Burning or other methods of residue disposal conceivably could reduce the abundance of natural control agents and lead to increased damage by pests. Generally, however, little is known about how residue treatments might enhance effectiveness of a pest's natural enemies.

Some residue treatments, particularly those involving fire, severely affect insects and other arthropods having active roles in recycling minerals back to the soil. As noted by Ovington (1968), nutrients held in the forest's organic matter may represent much of the site's readily available nutrient capital. Consequently, initiation of residue recycling by agents such as insects, mites,

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5/ J.H. McGhehey. The biologies of two hemlock bark beetles in western Oregon. M.S. thesis, Oregon State University, Corvallis, 1967.

Figure 4.--Deterioration of Douglas-fir killed 4 years previously by the Douglas-fir beetle. Rot penetrating inward was introduced by the beetle.

Figure 5.--Ambrosia beetle galleries and blue stain fungus penetrating deep into the wood of ponderosa pine a few weeks after beetle attack.

and diplopods, is important for the long-term health of the forests (Bollen 1974). Mineral cycling is an intricate process involving first fragmentation of dead material into smaller and smaller pieces, then decomposition into compounds which enrich the soil (Moore and Norris 1974). Decomposition itself is largely a microbial process; but its success depends heavily on frasmentation of the material, which is largely an arthropod process (Witkamp 1971).

Bark beetles initiate the fragmentation process by loosening the bark and introducing wood-destroying fungi into logs and limbs (Graham 1925) (fig. 4). This is followed by a progression of other arthropods, each contributing to the fragmentation of the material (Wickman 1965, Elton 1966). Following bark beetles are wood borers such as ambrosia beetles (Scolytidae) (fig. 5), flat- and round-headed borers (Buprestidae and Cerambycidae), termites (Isoptera), horntails (Siricidae), carpenter bees (Apidae), and carpenter ants (Formicidae). These insects bore holes deep into the wood and also introduce wood-destroying fungi (Boyce 1923, Shea and Johnson 1962, Wright et al. 1956, Wright and Harvey 1967, Kimmey and Furniss 1943). Advanced deterioration is aided by wood roaches (Phyllodromidae), crane flies (Tipulidae), and numerous beetles (Kuhnelt 1961).

The last arthropods to attack are the more cryptic species generally found in the organic layer of the forest floor, such as the springtails (Collembola), oribatid mites (Oribatei), and millipedes (Diplopoda) (Elliot 1970, Crossley and Bohnsack 1960, Naglitsch 1963). Price (1973), in a study of the fauna in the organic and upper soil layers under a ponderosa pine stand near Grass Valley, California, showed a population density of about 200,000 arthropods per square meter of forest floor. About 150 species were encountered, dominated by mites (mostly oribatids) and followed by springtails. What appears to be even larger populations were recorded by Vlug and Borden (1973) under a mixed stand of western hemlock and cedar in southern British Columbia.

Edwards et al. (1970) and Kowal (1969) noted that decomposition proceeds slowly when the litter fauna is excluded. Among the reasons for this is that fragmentation may increase the exposed area of organic material on the ground up to 15 times its original surface area (Witkamp 1971). Also, the fecal material of fragmenters encourages growth of decomposing microbes, particularly bacteria (Crossley 1970). Fecal pellets also encourage increased moisture-holding capacity and decreased evaporation to one-third that of undigested litter (Witkamp 1971). Moisture, in turn, further encourages arthropod and microbial populations.

The question facing foresters is whether the beneficial aspects of insect fragmentation outweigh the reasons for removing residues. If residues are removed by broadcast burning, for eyample, then presumably some pest problems will be removed and decomposition (through rapid oxidation) will occur anyway (Hall 1972). A light burn typically removes only the fine fuel, leaving many islands of unburned material. This type of burn would probably be compatible with the concept of preserving the fauna of the forest floor. The hard burn favored by most foresters, on the other hand, could remove much of the fragmenting arthropod population. Huhta et al. (1967) in Finland and Vlug and Borden (1973) in British Columbia both noted reduced arthropod populations following slash burning. Also, the soil environment may be so changed that reinvasion by the soil fauna could be greatly delayed. Karppinen (1957), for example, found in Finland that the number of oribatid mites remained reduced 27 years after burning. Huhta et al. (1969) also noted low oribatid populations 7 years after burning but also observed a greater than normal population of other mites and Collembola in the burned area.

Prescribed burning before timber harvest is also a technique for reducing residue accumulations. Metz and Farrier (1973) checked the effects of periodic and annual burnings on the fauna under loblolly pine *(Pinus taeda* L.) stands in South Carolina. They found that periodic burnings at 3- or 4-year intervals did not significantly reduce arthropod populations on the forest floor but that annual burnings were destructive to these animals. Buffington (1967), checking the effects of a wildfire in the pine barrens of New Jersey, found reduced arthropod populations 1 year after the fire.

There are, of course, slash treatments which are alternatives to broadcast burning. Slash could be scraped together and burned in piles. This treatment, because it greatly reduces both food and cover, would probably drastically reduce arthropod populations on the forest floor. Crushing slash should improve the environment for arthropods by putting the material closer to the soil where there is a higher, more preferred moisture level. Burying slash may also speed deterioration for the same reason, provided the wood were not put so deep that it would discourage arthropod attack--more than 3 inches (7.6 cm) would probably be too much. Also, delaying such treatment until the wood borer population had an opportunity to attack the material would probably be wise.

Chipping slash may be one of the best treatments. It eliminates not only the residue and pest problems but also the need for many of the insect fragmenters. Whether arthropod populations living in the organic layer could survive even this treatment, though, is anybody's guess. There is no information on what to expect. Presumably, just cutting timber antagonizes litter populations to some degree because of the increase in heat and reduction in moisture at the duff level. Most arthropods found on the forest floor are found in humid, cool conditions; in general, the optimum relative humidity is above 90 percent and the preferred temperature around 15° C (Schaller 1968). However, Huhta et al. (1967) found in Finland that the changes in the soil fauna as a result of clearcutting were not too significant. There was a decrease in the number of individuals, but the same species were dominant--the number of species, in fact, increased because of an influx of new ones.

Complete removal of slash from an area through 100-percent tree utilization solves many problems but leads, ultimately, to impoverishment of the site (Moore and Norris 1974). This would mean that each rotation of trees would come under increasing nutrient stress. Historically, pest problems have thrived on stress and would ultimately take advantage of a nutrient-poor forest. In Europe, for example, some stands with a history of repeated removal of litter in clearcuts have been observed to be either chronically infested with forest pests or predisposed to recurrent mass infestations (Francke-Grosmann 1963). Several European investigations show that pest populations are greatly reduced in stands treated with mineral fertilizers (Buttner 1961; Schwenke 1960, 1961; Plerker 1965).

CONCLUSIONS

There is no doubt that residues can generate pest problems. Trees damaged by storms or fire, particularly in the Douglas-fir subregion, can produce enormous bark beetle populations that kill thousands of trees. Well-timed salvage is the best solution to this problem when the affected area is localized. Often, though, the damage is too widespread to make any treatment practical. Other solutions are seriously needed but unavailable at this time. Recent discovery of a chemical that repels Douglas-fir beetle populations suggests a possible solution (Rudinsky et al. 1972).

The pine engraver beetle problem associated with precommercial thinning slash of ponderosa pine is unpredictable but nevertheless of great concern. The slash cannot be burned in place because it is too green to burn at the time it is attractive to beetles. Chipping the slash before the beetle attack is a possible alternative. The fresh chips may attract a few beetles to the area. But, without a suitable habitat, the initial brood would not produce the attractants (pheromones) that would cause a strong secondary attack.

The problem of the balsam woolly aphid attacking advanced silver fir reproduction makes it mandatory that the understory trees be removed after logging and provision be made for reconversion to Douglas-fir. To date, the best solution *to* this problem has been to burn the slash and then seed or plant to Douglas-fir.

As pressing as these problems are, however, the threat of outbreaks posed by insects breeding in residues is generally overrated. From the entomological point of view, most residues in the Pacific Northwest, particularly slash, do not need treatment to prevent pest outbreaks. Graham (1922) and Craiphead et al. (1927) long ago concluded that the insect menace posed by slash is more theoretical than real. Entomologists today, with considerably more empirical evidence behind them, generally agree. Although hundreds of insect species breed in slash, relatively few are capable of injuring living trees. Some kinds of slash, such as from hemlock, true fir, larch, and cedar, rarely produce pests affecting living trees in Oregon and Washington. Other types of slash, notably from harvests of Douglas-fir, ponderosa pine, and Sitka spruce, have the potential to create problems but, as yet, there have been no documented cases of their doing so in the Pacific Northwest.

In most cases, the best entomological practice appears to be *to* preserve beneficial insects whenever possible. Generally that would mean leaving slash untreated. It may also mean changing harvest methods from clearcutting to selection or shelterwood cutting to maintain moisture and reduce heat where populations live on the forest floor. However, the best practice needs identification by research. Huhta et al. (1967) found that soil fauna populations in clearcuts were greater than in thinning areas. They speculated that the small amount of food and shelter derived from debris in thinning soon disappeared and the climatic extremes at the forest floor were accentuated by the lack of a closed canopy.

Clearly, much research is needed on the relationships' between insects and residues and the health of the forests. At this time, the most important questions seem to be:

1. Can biological assessments for the Douglas-fir beetle and pine engraver beetle be developed for accurately predicting damage impact for any given situation? Spending time and money for crash residue removal programs when they are unneeded is a great waste.

2. Is residue a refuge for the significant number of parasites and predators which attack pest species, and are they important? If not, this factor can be eliminated from the decisionmaking process of what to do with residues.

3. Do the miscellaneous bark beetles and borers found in residue significantly speed deterioration of logs, limbs, and bark? An answer will help decide the need for slash disposal and possibly suggest how deterioration might be

increased by manipulation of insect populations and forest environment. Current research at the University of Washington suggests that certain biochemical changes may be responsible for attracting a wide range of insect consumers to forest debris of different ages. Accordingly, if man could synthesize these chemicals, he could hasten deterioration by increasing the consumer population./

4. Does the fauna on the forest floor play a significant role in mineral cycling; and if so, is it able to survive in clearcut areas; or is it better adapted to selection or shelterwood cutting? Also, would soil fauna populations suffer greatly from a series of light underburnings to reduce residue accumulations in established stands? These seemingly insignificant animals should not be ignored in either the harvesting system or residue treatments if they are as important as some studies suggest.

5. Is the fauna on the forest floor displaced by slash burning or chipping of residues and, if so, how rapid is reinvasion? Is rapid reinvasion necessary? We must be able to evaluate the consequences when forced to take measures which may be undesirable from the standpoint of arthropod populations.

Answers to most of these questions would involve research into both population dynamics and forest energetics. That generally means a rather sizable research commitment in time, probably 5 to 10 years per study. Some work of this type has already been initiated, but a much greater commitment is needed to make a significant impact on the research needs.

Besides a greater commitment in time and money, insect research of this nature needs a revised concept of what constitutes beneficial insects. The tendency of foresters and entomologists has long been to consider insects as either pests or enemies of pests. In this frame of reference, other insects become nonentities. It is increasingly apparent, though, that nature has use for all insects. And often the connection of the "other insects" with the needs of man are not as complicated as they are subtle. What would happen, for example, if twig borers were eliminated from the Douglas-fir? Would we still have the clean stems so typical of Douglas-fir? If we eliminated the miscellaneous defoliators from the tree crowns, would the micro-organisms responsible for mineral cycling miss the substrate provided in fecal pellets? Would, then, rapid tree growth begin to slow at age 25 instead of, say, 50 years? Many cultural activities, such as residue treatments, affect such obscure insects. So then we come back to research needs. Since insect enemies are often rather apparent, the critical question in residue research may be--which are our friends?

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DISEASES

E.E. Nelson and G.M. Harvey

ABSTRACT

Forest residues, produced in quantity by various disease agents, often are instrumental in continuation of disease. Root rots are especially tied to saprophytic survival in forest residues, mainly stumps and root systems. Other diseases, though producing considerable residue, are less dependent upon it for continued disease development.

Three root pathogens, **Armillaria mellea, Fomes annosus,** *and* **Poria weirii,** *are responsible for the bulk of root rot mortality in the Pacific Northwest. Where these fungi are established in stumps and root systems, damage will occur to surrounding trees.* **F. annosus** *can infect stump surfaces as well and presents an additional danger in managed stands. Where damage is heavy from any of these agents, consideration should be given to stump removal if practical.*

Rhizina undulata *damages seedlings planted where logging slash or other materials were previously burned. Disposal of residues by burning, then, can create disease problems, but in most instances there is no disease problem.*

Other than root diseases, forest disease problems are seldom aggravated by forest residues.

Keywords: Forest disease (root rots)--*Poria weirii, Armillaria mellea, Fomes annosus, Rhizina undulata.*

INTRODUCTION

Residues occur in natural forests (forests not intended for timber harvest) from a number of causes. Litter accumulates constantly; branches and tops fall from wind or snow load; whole trees die, fall, and ultimately rot on the forest floor. The accumulation of residues generally does not increase indefinitely in Pacific Northwest forests because at some point natural residues are incorporated into the soil at approximately the same rate as they are added. Before this state of equilibrium is reached, an undesirable quantity of residue may accumulate where normal decay is retarded.

Disease is one of several factors contributing to residue production, sometimes in catastrophic proportions. In the Pacific Northwest, cull and mortality losses from disease (nearly all of which become forest residue) each year exceed 240 million cubic feet (6.8 million cubic meters) (Childs and Shea 1967). These residues are similar to those produced in most other ways. In natural forests, all trees eventually die and decay, so diseases of living trees are of consequence to man only insofar as they may cause inconvenience, fire hazard, or danger for recreational use. In managed or unmanaged forests that will someday be harvested, disease is important primarily because many of its residues could otherwise be used by man. In some cases these residues may serve to perpetuate the disease. In addition, residues impede travel, are safety and fire hazards, and may lead to erosion, bark beetle infestations, and problems in regeneration. Many "diseased" areas are unsuitable for recreational development and may be unattractive for any recreational use. Disease decimated areas can, however, provide suitable habitat for many kinds of wildlife.

Forest diseases can be divided conveniently into four categories: diseases of foliage, diseases of stems (excluding heartrots) and branches, heartrots, and diseases of roots. Ordinarily, foliage disease residues are not problems. Foliage, lost prematurely, causes only a temporary buildup in flammable litter. Prolonged, severe disease conditions over several years, however, can cause mortality which results eventually in an accumulation of whole-tree residues.

Diseases of stems and branches are caused primarily by obligate parasites (e.g., dwarf mistletoe, rust fungi, and some canker fungi). Many of these parasites cause growth abnormalities such as large "witches brooms" or galls in tops and branches which sometimes become so contorted and reach such massive proportions that when they reach the forest floor they remain for years as obstructions to travel and as fire hazards. Dwarf mistletoe alone accounts for 72 million cubic feet (2 million cubic meters) of mortality annually in the Pacific Northwest (Childs and Shea 1967).

Heart rots and most of the important root diseases in the Pacific Northwest are caused by wood-destroying fungi (Basidiomycetes). They produce whole or nearly whole tree residues when trees are broken at rot-weakened areas of the main stem or major roots below ground. Over 150 million cubic feet (4.25 million cubic meters) of residues result from heart rot cull and root rot mortality each year (Childs and Shea 1967). Windthrown, root-, or butt-rotted trees are frequently jackstrawed in the woods and present problems in mobility; however, these trees or parts of them are already decayed and probably will return to the soil faster than residues of comparable size produced by other destructive agents.

Many diseases are cyclic in nature and result in periodic accumulation of forest residues. At times, residues may be produced in abnormally large proportions when new pathogens are introduced or unsuited species or seed sources are used in reforestation, but many diseases remain at endemic levels throughout the history of the stand.

Residues resulting from a disease often are important in continuation of that disease. Fruiting bodies of certain foliage diseases mature on the ground and produce inoculum which infects developing foliage above. Wood decay organisms similarly produce spores from structures developing on fallen trees and slash. Root diseases are often strongly dependent upon stumps and roots left in the soil, or upon rotted butts lying in contact with the forest floor, as reservoirs of inoculum for renewed infection.

Treatment of these residues could drastically change the development of diseases in areas of residue accumulation, especially from certain root diseases. Finding the most beneficial treatment within the limits of practicality will challenge the researcher, engineer, and practicing forester alike.

INFLUENCE OF RESIDUES AND RESIDUE TREATMENTS ON SPREAD AND CONTROL OF DISEASE

Though many diseases depend on forest residues, probably in no other forest disease category is this more important than in root diseases. The saprophytic phase as it exists in woody tissues of no longer living hosts is essential to the completion of the disease cycle for major root rot fungi in the Pacific Northwest. In addition, the existence of residues produced in numerous other ways rapidly intensifies root disease hazard by greatly increasing possibilities of saprophytic colonization. Most important forest root pathogens are able to use both cellulose and lignin and consequently can successfully compete with other organisms for these available woody substrates.

No matter at what stage forest residues are colonized, such residues are potential root disease problems only if the pathogen is able to survive in them and if susceptible hosts come within reach of the pathogen. Survival of the pathogen itself depends on many factors, among which are size and position or location of residues, various soil factors, and protective mechanisms of the particular fungus. Again, chance of infection depends on a number of factors, such as tree species present, proximity to colonized residue, host vigor, adaptive mechanisms of the pathogen, and various soil factors. Each pathogen reacts somewhat differently from others. For a more indepth discussion, three of the most important root pathogens will be discussed separately.

ARMILLARIA MELLEA

Armillaria mellea is known worldwide and is present in all major forest types in the Pacific Northwest. For successful pathogenesis, *A. mellea* depends upon a substantial food base and trees under stress (Leaphart 1963). Living trees or forest residues may become food bases after successful attack and colonization. Once colonized by the fungus, these food bases become centers of infection as specialized fungus strands (rhizomorphs) radiate outward in the soil and infect nearby trees (fig. 1). Younger trees are most susceptible; older trees of good vigor are seldom killed. Singh (1970) found about half of 2,400 seedlings (*Pinus glauca* and several exotic species) killed by *A. mellea* in a 10-year-old plantation. He attributed the rapid killing to nutrient deficiency (a stress), low vigor of exotics, and the large amount of inoculum in stumps left from the previous stand. Conifers are killed more easily than hardwoods, but colonized hardwoods provide excellent food bases for infection of adjacent trees (Patton and Bravo 1967).

One can expect *A. mellea* to be more of a problem in young stands subject to silvicultural practices such as thinning, especially if hardwoods are present or trees to be left are of low vigor or subjected to environmental stress. Damage to the remaining stand is likely to be greatest soon after thinning when numerous stumps are colonized but declines with exhaustion of food base and increased vigor of released uninfected trees. Any wood residue buried or partially buried in the soil may be colonized by *A. mellea*. The larger the residue, the more likely it will be an effective source of inoculum.

Figure 1.--*Armillaria mellea in ponderosa pine stumps infects and kills young pine trees in the vicinity.*

Gibson (1960) found that pine plantations following hardwood stands were much more susceptible to *A. mellea* than those following conifers. Thinning in pine or reforestation following pine was not considered a problem except immediately after the operation since pine stump deterioration was rapid. Adams (1972) has clearly demonstrated the association of residual ponderosa pine stumps and *A. mellea* mortality in young ponderosa pine in central Oregon.

In natural forests, one can expect increased damage from *A. mellea* when the number of weakened and dead trees is greatly increased, e.g., by extensive snowbreak, insect damage, and consecutive years of defoliation. Severe drought or other debilitating factors might likewise benefit the pathogen (Leaphart 1963).

A. mellea is a "pathogen of opportunity." When trees encounter considerable stress or where large amounts of food are opened to colonization (as in a thinning), the fungus may become a problem, at least for a short time. Keeping trees vigorous is the best insurance against losses by *A. mellea*.

FOMES ANNOSUS

Fomes annosus, like *A. mellea*, is well known around the world in the temperate zone (Powers and Hodges 1970). Its host range is large--it attacks both conifers and hardwoods. Much work has been done on the pathogen in Europe and in the Eastern and Southern United States, especially on pine. In species other than pine, decay of heartwood is probably more serious a problem than mortality.

In the Pacific Northwest, *F. annosus* is found on many coniferous species but has not been considered a serious disease except on western hemlock. Old-growth hemlock is often butt-rotted with *F. annosus,* and scars on young hemlock are often infected by this fungus (Hunt and Krueger 1962).

Infection of stumps by basidiospores is a problem in forest management both in Europe and in Eastern United States. Driver and Wood (1968) found a high rate of stump infection in western hemlock in western Washington (50-90 percent). Driver et al. (1970) further found that thinning hemlock with herbicides did not prevent infection by *F. annosus.* Wallis and Reynolds (1970) showed that the fungus developing in inoculated stumps could grow into the roots and infect roots of living trees in contact. Douglas-fir was nearly as susceptible to spore infection as was hemlock.

Reynolds and Craig (1968) report an average high of 29-percent spore infection of Douglas-fir stumps in British Columbia from March to September. Infection of stumps was less common during winter months, perhaps because of a greater abundance of spores of *Peniophora gigantea* and *Trechispora brinkmanii*, antagonists of *F. annosus,* during this period. How this may relate to further disease development in the somewhat more resistant Douglas-fir is not known.

Typically, *F. annosus,* after colonizing the stump surface, grows into the roots at a rate of 3.3 to 6.6 feet (1 to 2 meters) a year depending largely upon species and climate. The mycelium growing in the root and on its surface is able to penetrate roots of healthy trees when contact is made. In this manner, the disease may spread in the stand at rates of up to 1 meter (3.3 feet) per year (Hodges 1969). Although little information is available on made of spread in western hemlock, there is no reason to believe that the fungus acts significantly different than observed on other conifers. Wallis and Reynolds (1970) found growth of the fungus in stumps to be about 30 inches (76 centimeters) per year. Though western hemlock is probably our most vulnerable species, foresters should not disregard the possibility of damage to coniferous forests in any forest zone. Although much attention has been focused on disease development from infected stumps, other entry courts are available as well, especially in western hemlock. Many residues are subject to colonization, but only stumps and partially buried logs are likely to be of importance to disease continuation in either managed or natural forests. Again, the larger the buried residue, the greater the chance for it to be effective as a source of inoculum.

PORIA WEIRII

Poria weirii, probably the most destructive root pathogen in the Pacific Northwest, attacks all native conifers (fig. 2). *Poria ueirii* is principally a problem in west-side forests, especially where Douglas-fir predominates, but causes severe damage in some areas of high elevation mixed conifers as well. Its association with forest residues is much like that of *Fomes annosus.* Although the role of spore infection is not well known and certainly does not approach the magnitude of *F. annosus,* this pathogen seems to possess an amazing potential to survive in forest residue: many instances have been reported of survival for 50 years or more in stumps and root residues of old-growth forests. One report estimates survival may continue more than a century (Childs 1955). The potential of *P. weirii* to colonize forest residues is open to question. The fungus lacks the ability of *A. mellea* to grow through the soil (no rhizomorphs produced) to encounter these residues; however, Wallis and Reynolds (1965) demonstrated that *P. weirii* was able to invade stumps of trees felled at least 12 months earlier and Douglas-fir heartwood buried 12 months in the soil.

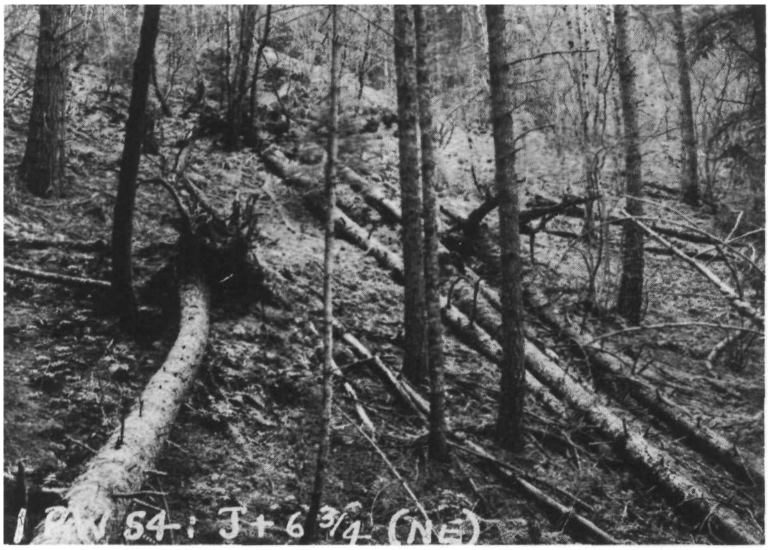

Figure 2.--Residues created by ***Poria weirii*** *in young Douglas-fir. The pathogen surviving in the roots of fallen trees will infest remaining trees or others establishing themselves in resulting openings.*

When roots of living trees encounter the fungus in dead or decaying roots and stumps, they become infected. *Poria* grows over the surface of the'root, penetrating the bark and colonizing the wood in much the same way as *F.* ***annosus.*** Its ability to decay heartwood often leaves a stricken tree symptomless until windthrown. In managed *Poria*-infected stands, thinnings often leave apparently healthy trees--only to be lost to windthrow when the canopy is opened in the thinning operation. When stands are clearcut, regeneration around decayed stumps becomes infected, and spread continues from tree to tree at root contacts. Logging debris other than stumps is probably of minor importance in disease continuation unless it contains *P.* ***weirii*** when cut and is buried or partially buried in the operation.

Present residue disposal methods seem to have little effect on the major root pathogens discussed here. Very seldom are burns hot enough to destroy appreciable amounts of buried inoculum in colonized roots, at least at their greater depth in soil.

RHIZINA UNDULATA

When residues are burned to eliminate large amounts of wood fiber from the site or to eradicate brush Competition, another root disease caused by *Rhizina undulata* may cause concern in regeneration of the site. Although not presently a major problem, it is important on certain sites in the Douglas-fir region and, because it kills very young trees, may be more important than is apparent.

Morgan and Driver (1972) have repeatedly found the disease in western Washington, but a survey of National Forests in Washington and Oregon showed negligible damage (Thies 1973). In Finland, *Rhizina* sometimes causes very heavy damage in plantations on burned areas and is considered a serious forest disease (Laine 1968). High soil temperatures are necessary to germinate ascospores of this fungus which proceed to colonize woody materials saprophytically and to attack seedlings on the site. In Great Britain, the disease is thought to be significant only for about 4 years after burning (Jalaluddin 1967). Ginns (1968), however, thinks that environmental conditions in British Columbia may be more favorable to disease development. The disease is only of recent concern in the Pacific Northwest, and its full potential is not yet known. Thus far, only coastal areas of the region are involved. Obviously, other less important root diseases play similar but lesser roles involving forest residues. Their total importance as recognized presently is not great enough to merit discussion here.

In all the vegetation zones of the Pacific Northwest, ubiquitous but usually unimportant foliage diseases exist which are normally of slight economic importance to their native coniferous hosts. Since foliage diseases tend to be cyclic, usually with weather, their relative importance changes from year to year. Causal fungi include *Lophodermium* spp. causing needle casts of *Abies, Larix, Libocedrus, Pinus,* and *Tsuga;* and *Herpotrichium* spp. or *Neopeckia* sp. causing brown felt blights of *Abies, Juniperus, Picea, Pinus, Pseudotsuga, Taxus, Thuja,* and *Tsuga*. They are capable of sporulating on infected foliage which has fallen to the ground and thereby not only continue or intensify a flammable residue buildup but reinfect and cause growth loss of conifers as well[1] (Hepting 1971, Boyce 1961).

DISCUSSION, NEEDS, AND RECOMMENDATIONS

No one can doubt the importance of forest disease as a producer of residues. These residues in turn support the disease agent during the absence of a susceptible host and are, indeed, necessary for continued disease development. The special ability of wood-rotting fungi to digest cellulose and often lignin as well and their capability to penetrate thick layers of corky bark keep them secure from the intense competition found on simpler substrates in the soil and allow these pathogenic organisms to do remarkably well in the saprophytic phase (Garrett 1970).

Without the ability to survive for many years in forest residues, such destructive pathogens as *Poria weirii, Fomes annosus,* and *Armillaria mellea* would drop from the list of important disease problems to mere annoyances. Some fungal adaptation and some substrate factors are important in determining how long a fungus might survive in woody residues. Many root rot fungi are capable of forming black psuedosclerotial barriers (zone lines) which support favorable conditions for the fungus within and keep antagonists out. The substrates themselves vary in size, condition of bark and wood, and location in the soil. One might expect longer survival if bark were intact, residue large, resin pockets common, and wood not in a highly advanced stage of decay. All these things are important in root pathogen survival, and most can be altered by the action of man.

1/ J.M. Staley. Personal communication to Earl E. Nelson, 1972.

Forest tree pathogens which attack foliage and sporulate on the fallen needles are likewise vulnerable to regulation through forest practice. Though these fungi are normally of questionable importance, they may become serious when climatic conditions are favorable. Residues caused by obligate parasites such as rusts or dwarf mistletoe do not contribute to disease buildup. Heart rotting fungi may sporulate on forest residues but probably no more so than if these trees were left standing.

The dilemma of the forest pathologist is often that he, after careful study and diagnosis of a disease problem, must tell the forest manager that there is no economically feasible solution. Often the only advice is "don't do anything, save your money," or "ignore it, go ahead with your plan." Although better than no advice at all, it falls short of solving the problem.

Regarding root disease in general, thinning in root rot areas is not desirable unless damage is at a low level, volume of salvage warrants the operation, or young stands are so stagnated that future root rot losses are likely to be dwarfed by increased growth of more vigorous released trees. Since the major root rot fungi survive in infested residues and in some cases are likely to invade logging residues, some consideration should be given to their removal or destruction or both. Stumps are by far the greatest threat. When practical, infested stumps can be removed and piled, piled and burned, or chipped. This in effect removes the inoculum from the site, destroys the inoculum, or converts it to a state much more susceptible to competition from soil microbes. When species highly susceptible to *Fomes annosus*, such as western hemlock, are thinned, consideration should be given to treating **stump** surfaces and avoiding injury to residual trees even if *F. annosus* is not present on the site.

Residue treatment recommendations after final harvest are similar to those for thinning. Where possible, infected residues (principally stumps) should be removed as above. Care should be taken to avoid burial of infected long-butts or other material during logging or slash disposal. These recommendations will probably greatly reduce disease problems, but their cost may prohibit implementation.

Elimination of brush on a harvested area not only reduces competition between the brush and young trees but reduces cool, moist microsites provided by dense brush cover which are conducive to foliage diseases. In areas where foliage problems exist, this factor should be considered. Controlled burning in established stands to reduce inoculum of certain needle fungi may be desirable under some conditions but, in most instances, will not be warranted and probably could be used only on a small proportion of problem sites.

Limited knowledge of root disease-forest residue interrelationships makes it difficult to provide adequate recommendations to the practicing forester. Studies now underway will provide some answers, but still more work will be required and new methods and equipment will have to be devised. Studies presently underway in the Pacific Northwest dealing with residues or their treatment as disease factors include:

1. Effect of stump removal and soil scarification on *Poria weirii* disease development in regeneration--Pacific Forest Research Centre, Canadian Forestry Service, Department of the Environment, 506 West Burnside Road, Victoria, B.C., Canada

2. Effect of fertilization and timber type on survival of *Poria weirii* in buried wood--Forestry Sciences Laboratory, Pacific Northwest Forest and Range Experiment Station, 3200 Jefferson Way, Corvallis, Oregon 97331.

3. Infection potential of *Poria weirii* basidiospores on stumps and tree wounds--Forestry Sciences Laboratory, Pacific Northwest Forest and Range Experiment Station, 3200 Jefferson Way, Corvallis, Oregon 97331.

4. Potential of *Fomes annosus* to infect hemlock roots from invaded stumps--Pacific Forest Research Centre, Canadian Forestry Service, Department of the Environment, 506 West Burnside Road, Victoria, B.C., Canada.

5. Food base requirements for *Armillaria mellea* root disease development in ponderosa pine--Plant Pathology Department, Oregon State University, Corvallis, Oregon 97331.

6. Occurrence, diagnosis, and management alternatives concerning *Rhizina* root rot of planted Douglas-fir--College of Forest Resources, University of Washington, Seattle, Washington 98195.

Additional studies could tell us:

1. Root rot hazard from cull logs left or buried on the site.

2. Effects of severe fires on root pathogen survival and infection in regeneration.

3. Potential for residue colonization by basidiospores of *P. weirii*, *A. mellea*, and *F. annosus*.

4. Effects of chipped slash (incorporated into soil or layered on the soil surface) on development of disease in regeneration.

5. Effects of thinning in ponderosa pine on root disease caused by *F. annosus* and *A. mellea*.

Stump removal holds promise in reducing *P. weirii* damage in regeneration (Weir and Johnson 1970). If time proves this method of control successful, more effective and economical methods of accomplishing this job will be necessary, especially on steep slopes. Chipping of residues to reduce disease development will also call for more efficient and less costly machinery for operation on varied topography.

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APPENDIX

GLOSSARY

adsorption complex--The group of substances in soil capable of adsorbing other materials. Organic and inorganic colloidal substances form the greater part of the adsorption complex; the noncolloidal materials, such as silt and sand, exhibit adsorption but to a much lesser extent than the colloidal materials.

advance reproduction--Young trees that have become established naturally in a forest before cutting or regeneration operations.

aerial fuel--All burnable material more than 6 feet (1.83 m) above the ground. This includes the upper portions of trees, large shrubs, snags, and all the foliage and epiphytes on them. Compare ground fuel.[1/]

aerial logging--Yarding methods in which logs are suspended above ground from a helicopter, or from skyline or balloon cable systems. Compare cable logging, skyline logging, tractor logging.

aerosol--A colloidal system in which the dispersed phase' is composed of either solid or liquid particles of no greater than 1-micron diameter, and in which the dispersion medium is some gas, usually air. Haze, most smokes, and some fogs and clouds may be regarded as aerosols.

agglomeration--The growth of an airborne particle by collision and assimilation of other particles.

aggregation--The binding together of individual soil particles into larger, compound ones as by organic matter, iron hydroxides, or fungal hyphae.

albedo--The fraction of incident light or electromagnetic radiation reflected by a body. The albedo is distinguished from reflectivity, which refers to one specific wavelength.

allelopathy--Repressive effect of plants upon each other, exclusive of micro-organisms, by metabolic products, exudates, and leachates.

amenity--The attractiveness and esthetic or nonmonetary value of real estate. (Applied to qualities of the forest and landscape that appeal to the recreationist.)

ammonification--Decomposition of nitrogen-containing organic compounds to produce ammonia or ammonium compounds. Compare nitrification.

area burning--See broadcast burning.

area ignition--For prescribed burning, fire sets in many places throughout an area either simultaneously or in quick succession and so spaced that the entire area is rapidly covered with fire. Compare strip burning.

artificial regeneration--The renewal of a tree crop by direct seeding or planting. Compare natural regeneration.

[1/] Underlined terms are defined elsewhere in this glossary.

autotrophic--Organisms that manufacture their own food exclusively from inorganic substances occurring in soil, air, or water.

available fuel--The portion of the total combustible material that fire would actually consume under given conditions.

available moisture--The water in the soil that can be readily absorbed by plant roots.

available nutrient--That portion of any nutrient in the soil that can be readily absorbed and assimilated by growing plants.

backing fire--A prescribed fire or wildfire burning into or against the wind or down the slope without aid of wind. Compare head fire, running fire.

balloon logging--An aerial cable yarding system in which the logs are suspended beneath a balloon. Compare cable logging, aerial logging.

basal area--The area of the cross section of a tree at breast height; for a stand, the total basal area per unit of area, usually per acre.

below-cloud scavenging--See washout.

biomass--Total quantity of living organisms per unit area including stored food.

broadcast burning--Intentional burning in which fire is set to spread over all of a specified area, usually in nonpiled fuels. In the Pacific Northwest, usually confined to the area burning of logging slash following clearcutting.

brown rot--Any wood rot that attacks the cellulose and associated carbohydrates leaving the lignin, producing a light to dark brown friable residue, hence, loosely termed dry rot.

browsing--Feeding on the buds, shoots, and leaves of woody growth by livestock or wild animals.

brush blade (also, brush rake) --A bulldozer bladelike attachment with long teeth specially suited to ripping out and piling brush with minimum inclusion of soil.

brushfield--A more or less temporary vegetative type, primarily of shrub species, that occupies potential forest or grass site.'

buildup index--A measure of the cumulative drying of fuels as the fire season progresses.

burying--A residue disposal treatment in which residue is collected, placed in a large pit or trench, and covered with soil; usually done with a tractor.

cable-directed felling--A method of directional felling wherein a cable is attached to the tree and tightened to control direction of felling, prevent runaway logs on steep slopes, and increase control over the felling of leaning trees. Also called tree pulling.

cable logging--Yarding of logs from stump to loading area by any of various cable systems that may or may not lift any or all of the log from the surface. Compare aerial logging, tractor logging, high-lead logging.

carbon cycle--The sequence of transformations whereby carbon dioxide is fixed in living organisms by photosynthesis or by chemosynthesis, liberated by respiration and by the death and decomposition of the fixing organisms, used by heterotrophs, and ultimately returned to its original state.

carbon-nitrogen ratio--The ratio of the weight of organic carbon to the weight of total nitrogen in a soil or in organic material. It is an indicator of soil processes and fertility.

casehardening--A condition in which the surface layer of a log is harder than the interior.

cation exchange--The interchange of cations between a solution and the active soil material such as clay. Common soil cations are calcium, magnesium, sodium, potassium, and hydrogen.

chipping--1) In residue treatment, the reduction of woody residue by a portable chipper to chips that are left to decay on the forest floor. 2) In utilization, the conversion of usable wood to chips, often at the logging site, for use in manufacture of pulp, hardboard, energy, etc.

clearcutting--A harvest and regeneration system, normally applied to an even-aged forest, whereby all trees are cut. Regeneration may be artificial or natural, logging methods may vary, and clearcut areas may be of any size.

climax community--The final stage of a vegetative succession through seral stages to the most stable, moisture- and shade-loving association the site can support.

coarse-textured soil--Includes sands, loamy sands, and sandy loams except the very fine sandy loam textured classes. Compare fine-textured soil, medium-textured soil.

commercial forest land--Land capable of or producing crops of industrial wood and not withdrawn from timber utilization. Productivity in excess of 20 ft^3/acre/yr (1.4 m^3/ha/yr) of industrial wood, Compare forest land.

conflagration--A raging, destructive fire. Often used to connote such a fire with a moving front as distinguished from a fire storm.

controlled burning--See prescribed burning.

convection--The transmission of heat by the mass movement of heated particles', as circulation in air, gas, or liquid currents. In meteorology, convection refers to the thermally induced, vertical motion of air.

convective smoke column--The thermally produced ascending column of hot gases and smoke over a fire.

cover type--The designation of a vegetation complex described by dominant species, age, and form. Compare forest type, brushfield.

crop tree--Any tree forming or selected to be a component of the final crop.

crown cover--The ground area delineated by the vertical projection of branches and foliage.

crown fire--A fire that advances from top to top of trees or shrubs more or less independently of the surface fire. Compare running fire.

crushing--Breaking and mashing of residue in place with heavy equipment including tractors and weighted rollers with cutting devices. Usually limited to brush, thinnings, and small slash. Serves to lower height of fuel and enhance its decay by increasing contact with the soil.

cull--A tree or log of merchantable size but classified as unmerchantable because of poor form, rot, or other defect.

damping off--The rotting of seedlings before or soon after emergence, by soil fungi attacking at soil level,

debris dam--A blockage, usually by forest residue, in the stream channel or along its side likely to be formed during high water. See flushout.

deflocculate--To separate or break up soil aggregates into the individual particles; to disperse the particles of a granulated clay to form a clay that runs together or puddles,

denitrification--The biochemical reduction of nitrate or nitrite to gaseous nitrogen either as molecular nitrogen or as an oxide of nitrogen.

desiccant--A drying agent or herbicide that kills tissues of living plants and causes them to lose moisture and dry out.

diurnal--Daily; pertains to daily cycles of temperature, relative humidity, wind, and stability.

duff--Forest litter and other organic debris in various stages of decomposition, on top of the mineral soil, typical of coniferous forests in cool climates where rate of decomposition is slow and litter accumulation exceeds decay. Compare F layer, humus, mor, mull.

dwarf mistletoe--Relatively inconspicuous flowering plants, parasitic on conifers, belonging to the genus *Arceuthobium* as opposed to the more conspicuous mistletoes in the genus *Phoradendron*.

ecesis--Establishment of an immigrant plant on a new site by germination, growth, and reproduction.

ecosystem--A community of plants, animals, other living organisms, and the non-living factors of their environment, whose interactions result in an exchange of materials and energy between the living and nonliving components of the system.

endemic--The normal population level of a potentially injurious plant, pathogen, parasite, or insect.

epidemic--Highly abnormal and generally injurious level of population of a potentially injurious plant, pathogen, parasite, or insect.

equilibrium moisture content--The proportion of moisture in a fuel particle attained when no further change occurs after exposure to constant conditions of relative humidity and temperature.

essential oils--Volatile substances found in different parts of many plants, including trees, which are separated by steam distillation and generally consist of mixtures of hydrocarbons, alcohols, esters, aldehydes, and ketones. Compare terpenes.

evapotranspiration--The combined loss of water from a given area due to evaporation from the soil surface and transpiration from plants.

even aged--Describes a forest stand composed of trees of about the same age, usually within a range of 20 years.

extra-period fire--A fire not controlled within a prescribed time limit; e.g., by 10:00 a.m. of the day following discovery.

fine fuels--The complex of living and dead herbaceous plants and dead woody plant materials less than one-fourth inch (0.6 cm) in diameter; fuels with a timelae of 1 hour or less.

fine-textured soil--Predominating in fine fractions, as fine clay. Includes all clay loams and clays. Compare coarse-textured soil, medium-textured soil.

fire behavior--The response of fire to its environment of fuel, weather, and terrain including its ignition, spread, and development of other phenomena such as turbulent and convective winds and mass gas combustion.

firebrand--Any source of heat, natural or manmade, that could start a forest fire, including burning material such as leaves, charcoal, sparks, or lightning.

firebreak--A natural or constructed strip or zone from which all fuels have been removed for the purpose of stopping the spread of fire or providing a control line from which to attack a fire.

fire climax--A plant association, forest type, or cover type held at a seral stage by periodic fires, therefore differing from the true climax community'; e.g., a Douglas-fir forest in the western hemlock zone.

fire damage--Monetary and other losses including damage to standing trees, forest soil, wildlife, watershed values, productivity, and recreational values.

fire danger--Resultant of both constant and variable factors--weather, slope, fuel, and risk--that affect the inception, spread, and difficulty of control of fires and the damage they cause.

fire hazard--A fuel complex defined by kind, arrangement, volume, condition, and location that forms a special threat of ignition, spread, and difficulty of suppression. Compare fuel type, risk.

fire hazard reduction--Any residue treatment that reduces threat of ignition, spread of fire, and its resistance to control. This may involve removal, burning, rearrangement, burying, or modification such as by crushing or chipping. Compare forest residue, fuel type.

fireline--A trail or strip cleared around a fire or area to be burned from which all flammable materials have been removed or treated to stop spread of the fire. Compare firebreak and fuel break.

fire retardant--Any substance that reduces flammability by chemical or physical action.

fire risk--The chance of a fire starting as determined by the presence and activity of causative agents; usually divided into man-caused risk and lightning risk.

fire season--The portion of the year during which fires are likely to occur, spread, and do sufficient damage to warrant organized fire control; strongly dependent on climate.

fire-size class--

Class A	spot to 1/4	acre	(1/10 ha)
Class B	1/4 to 10	acres	(1/10 to 4 ha)
Class C	10 to 100	acres	(4 to 40.5 ha)
Class D	100 to 300	acres	(40.5 to 121.4 ha)
Class E	300 to 1,000	acres	(121.4 to 404.7 ha)
Class F	1,000 to 5,000	acres	(404.7 to 2,023.4 ha)
Class G	5,000+ acres		(2,023.4+ ha)

fire storm--Fire-induced, violent, convective wind system within, around, and above a large continuous area of intense fire; often characterized by destructive force, surface indrafts, powerful updrafts, a towering convective smoke column, long distance spotting, and sometimes large fire whirls. Compare conflagration.

fire whirl--A spinning, vortex column of ascending hot air and gases rising from a fire and carrying aloft smoke, debris, and flame. Fire whirls range from a foot or two in diameter to small tornadoes in size and intensity. They may, involve only a hot spot within the fire area or the entire fire.

flash fuels--Fuels such as dried grass, leaves, draped pine needles, dead fern, tree moss, and some kinds of slash which ignite readily and are consumed rapidly when dry. Compare heavy fuels.

F layer (fermentation layer)--An upper soil layer of partially decomposed litter with portions of plant structures still recognizable. Occurs below the L layer <litter layer) on the forest floor. Compare humus.

flushout--A fast-moving wave of water, mud, rock,. and debris in a stream channel, caused by the breaking of a debris dam during a period of high water; a phenomenon of steep stream channels with heavy accumulations of debris in the channel and along its sides.

forest floor--All dead vegetable or organic matter, including litter and unincorporated humus, on the mineral soil surface under forest vegetation.

forest land--Land at least 10 percent occupied by forest trees of any size, or formerly having had such tree cover, and not currently developed for nonforest use. Compare commercial forest land.

forest protection--Prevention and control of any cause of potential forest damage.

forest residue--The unwanted accumulation in the forest of living or dead, mostly woody material that is added to and rearranged by man's activities such as forest harvest, cultural operations, and land clearing. Forest residue includes slash materials, excessive litter on the forest floor, unwanted living brush and weed trees, and standing dead trees and snags.

forest type--A classification of forest based upon the species forming a plurality of live tree stocking. Compare cover type.

fuel break--A strategically located strip or block of land of varying width, depending on fuel and terrain, in which fuel density has been so reduced as to provide an accessible location from which fires burning into it may be more readily stopped. The stand is thinned and remaining trees are pruned to remove ladder fuels; most brush, heavy ground fuels, snags, and dead trees are removed, and an open parklike appearance established in contrast to a firebreak from which all vegetation is removed. Compare with fireline.

fuel loading--The amount of fuel present expressed quantitatively in terms of weight of fuel per unit area. This may be available fuel or total fuel and is usually dry weight.

fuel type--An identifiable association of fuel elements of distinctive species, form, size, arrangement, or other characteristics that will cause a predictable rate of fire spread and difficulty of control under specified weather conditions.

glowing combustion--Oxidation of a solid surface accompanied by incandescence, sometimes evolving flame above it.

ground fire--Fire limited to the mantle of organic material, such as duff or peat, that accumulates-on top of the mineral soil. Characterized by glowing combustion and little smoke. Compare ground fuel.

ground fuel--All combustible materials below the surface litter, including duff, tree roots, punky wood, peat, and sawdust, that normally support a glowing combustion without flame. Compare aerial fuel.

harvest cut--The felling of the final crop in either a single cutting or a series of regeneration cuttings.

head fire--A fire spreading or set to spread with the wind. Compare backing fire, crown fire, running fire.

head of a fire--The most rapidly spreading portion of a fire's perimeter, usually to the leeward or upslope.

heart rot--Any rot characteristically confined to the heartwood, as with many ***Fomes*** and *Polyporus* species. It generally originates in the living tree.

heavy fuels--Fuels of large diameter such as snags, logs, and large limbwood that ignite and are consumed more slowly than flash fuels. Also called coarse fuels.

helicopter logging--An aerial logging system whereby logs are transported from the cutting area by helicopter.

herb--A flowering plant which does not develop a woody persistant stem but annually dies to the ground. Includes grasses and forbs.

heterotroph--An organism that cannot live without an external source of organic food.

high-lead logging--A method of yarding in which logs are dragged to the loading area by cable, usually in contact with the ground. Compare cable logging.

H layer--Layer occurring in mor humus consisting of well-decomposed organic matter of unrecognizable origin. Compare F layer.

holdover fire--A fire that remains dormant and undetected for a considerable time.

humification--The processes involved in the decomposition of organic matter leading to the formation of humus.

humus--That more or less stable fraction of the soil organic matter remaining after the major portion of plant and animal residues have decomposed; usually dark colored. Includes the F and H layers in undisturbed forest soils. Compare litter (L layer).

hydrocarbon--The simplest organic compounds composed of hydrogen and carbon. Hydrocarbons include gases, liquids, and solids and vary from simple to complex molecules. They are divided into alkanes or saturated hydrocarbons, cycloalkanes, alkenes or olefins, alkynes or acetylenes, and aromatic hydrocarbons.

hypha--The unit of structure of the fungi; a fungal filament.

ice nuclei--Any particles which serve as nuclei for the formation of ice crystals in the atmosphere.

ignition index--A number related to the probability of a firebrand starting a fire.

improvement cutting--Cutting in young stands to eliminate trees of less desirable species, form, and crown condition.

incinerator--An engineered apparatus used to burn waste substances and in which all the factors of combustion--temperature, retention time, turbulence, 'and combustion air--can be controlled. Varieties: open pit--open top with a system for placing a stream of high velocity air over the burning zone; and direct fed--accepts solid waste directly into its combustion chamber.

in-cloud scavenging--See rainout.

inoculum--Spores, mycelial fragments, and infected or infested material which can give rise to a new infection or infestation in previously uncolonized material.

intermediate cut--Any removal of trees prior to harvest cut.

inversion (temperature inversion)--A layer through which temperature increases with altitude; e.g., nighttime inversion above the ground. Aloft, an inversion layer separates warmer air above from cooler air below. This most stable condition inhibits vertical motion of air. Compare unstable air.

ion transport mechanism--See cation exchange.

ladder fuels--Provide vertical fuel continuity between strata as between surface fuels and crowns.

landing--Anyplace on or adjacent to the logging site where logs are assembled for further transport. See yarding.

latent heat--Energy absorbed or emitted in the state changes of water between liquid, vapor, and solid.

light burn--Degree of burn which leaves the soil covered with partially charred organic material; large fuels are not deeply charred. Compare moderate burn, severe burn.

light burning--Periodic broadcast burning to prevent accumulation of fuels in quantities that would cause excessive damage or difficult suppression in event of accidental fire. "Underburning" when done below an overstory.

lignin--One of the principal constituents of woody cell walls. It is considered to be responsible for the hardness and strength of cell walls in formation of wood.

litter (L layer)--The surface layer of the forest floor consisting of freshly fallen leaves, needles, twigs, stems, bark, and fruits. This layer.may be very thin or absent during the growing season.. Compare F layer, H layer.

littoral--Growing on or near a shore, especially of the sea. Compare riparian vegetation.

longwave (heat) radiation--Infrared radiation from warm objects, in contrast to shortwave (visible) radiation from the sun or other very hot objects.

lopping (also, lop and scatter)--Cutting branches, tops, and small trees after felling, so that the resultant slash will lie close to the ground. To cut limbs from felled trees.

macroclimate--The overall climate of a region, generally of a large geographic area. Compare microclimate.

medium-textured soil--Intermediate between fine-textured and coarse-textured soils. Includes very fine sandy loams, loam, silt loam, and silt-textured classes.

microclimate--The detailed climate of a very small site or habitat. Compare macroclimate.

micro-organism--Any organism of microscopic size, including bacteria, actinomycetes, fungi, algae, and protozoa. Also called microbes.

mineralization--Breakdown of organic compounds in soil; e.g., nitrogenous compounds such as proteins releasing inorganic constituents (in this case NH_4-, or -NO_4) that can be taken up by plant roots.

mineral soil--Term used in fire management to denote soil layers below the predominantly organic horizons; a soil that has little combustible material.

moderate burn--Degree of burn in which all organic material is burned away from the surface of the soil which is *not* discolored by heat. Any remaining fuel is deeply charred. Organic matter remains in the soil immediately below the surface. Compare light burn, severe burn.

moisture tension--The tension force with which water is held in the soil. It increases with dryness.

mopup, mopping up--Making a fire safe after it is controlled, such as by extinguishing or removing burning material along or near the fireline, felling snags, trenching logs to prevent rolling of embers, etc.

mor--In a forest soil, a layer of raw humus on top of the mineral soil with which it does not mix resulting in an abrupt demarcation between organic and mineral horizons. Compare mull.

mulch--Any loose covering on the surface of the soil whether natural (as litter) or deliberately applied organic materials (e.g., straw, foliage, chips).

mull--A humus-rich layer of forest soil consisting of mixed organic and mineral matter. Mull blends into the upper mineral layers without an abrupt change in soil characteristics. Compare mor.

mycelium--Mass of hyphae constituting the body of a fungus.

natural regeneration--The renewal of a tree crop by self-sown seeds or sprouts. Compare artificial regeneration.

natural resins--Secretions of certain trees, often exuding from wounds; obtained commercially by tapping the tree or by extracting with solvents. Compare oleoresin.

nitrification--The biochemical oxidation of ammonium to nitrite, as in soils by soil organisms. Compare ammonification.

nitrogen cycle--The sequence of biochemical changes undergone by nitrogen wherein it is used by a living organism, liberated upon the death and decomposition of the organism, and converted to its original state.

nitrogen fixation--The conversion of elemental nitrogen (N_2) to organic combinations or to forms readily utilizable in biological processes, as by soil organisms.

nurse crop--A crop of trees, shrubs (brush), or other plants introduced to shelter or naturally sheltering another and generally more important crop during its youth, by protecting it from frost, insolation,, or wind.

obligate parasite--An organism which can obtain food only from living tissue; cannot be grown in culture on nonliving media.

old-growth stand--Loosely defined as a condition in which rate of tree growth has passed its peak and normal processes of deterioration approach or exceed stand growth. In the Pacific Northwest, old-growth conifer forests are generally 150 to 300 or more years old and often contain large, dead, standing or down trees and partially decayed but still living trees. Accumulated natural residue and timber harvest slash are consequently often great.

oleoresin--A group of soft natural resins, consisting of a viscous mixture of essential oils (e.g., turpentine) and nonvolatile solids, secreted by the resin-forming cells of the pines and certain other coniferous and broad-leaved trees.

overstory--The trees, in a forest of varying heights, that form the uppermost canopy.

parent material--The mineral or organic mass from which the upper soil horizons develop.

partial cutting--Any forest harvest method that removes only part of the stand at any one entry as differentiated from clearcutting. Compare selection system, shelterwood system, thinning.

particulates--A component of polluted air consisting of any liquid or solid particles suspended in or falling through the atmosphere. Particulates are responsible for the visible forms of air pollution.

patch cutting--A type of clearcutting in which the cutting areas are of limited size (e.g., 2 to 200 acres (1 to 80 ha)) and are surrounded by forest, either uncut or young growth from an earlier cut. This gives a checkerboard or patchwork appearance, with size and shape of harvest area dependent upon terrain, forest condition, and logging method.

perception--The forest viewer's impression of what he sees, hears, or otherwise physically senses, as influenced by his experience, training, and beliefs.

pesticides--Chemical and biological agents used to control pests. Includes insecticides, herbicides, fungicides, rodenticides, and other biocides.

pheromones--Substances secreted by an animal to influence the behavior of other animals of the same species. For example, a chemical produced by an adult female moth to attract a male.

piling and burning--A forest residue treatment in which residue is gathered in piles and subsequently burned. Piling may be done by hand or machine depending on residue size, amount, terrain, and environmental limitations.

pioneer--A plant capable of invading bare sites, such as a newly exposed soil surface, and persisting there until supplanted by successor species. See ecesis, succession.

plastic limit--The minimum moisture percentage by weight at which a small sample of soil material can be deformed without rupture.

pole--A young tree of d.b.h. between 4 and 12 inches (10 and 30 cm).

preattack--A planned, systematic procedure for gathering, evaluating, and recording of intelligence, and constructing fire control facilities, to insure the rapid and efficient suppression of fire.

preattack--A planned, systematic procedure for gathering, evaluating, and recording of intelligence, and constructing fire control facilities, to insure the rapid and efficient suppression of fire.

preattack block--A unit of forest land delineated by logical and strategic topographic features for preattack planning.

precommercial thinning--Removal of immature trees to increase growing space and thereby growth rate of remaining trees. Done before the removed trees are large enough to have commercial value.

prescribed burning--Controlled application of fire to wild land fuels in either their natural or modified state, under such conditions of weather, fuel moisture, soil moisture, etc., as allow the fire to be confined to a predetermined area while producing the intensity of heat and rate of spread required to achieve certain planned objectives of silviculture, wildlife management, grazing, fire hazard reduction, etc. Compare broadcast burning, piling and burning, light burning.

prevention--Activities directed at reducing the number of fires. Includes public education, law enforcement, personal contact, and reduction of fire hazards.

progressive burning--Slash disposal by burning the slash as it is piled, usually as harvested trees are limbed and topped. Also called swamper burning.

progressive strip cutting--Clearcutting progressing against the prevailing wind in strips that are generally not wider than the height of the adjacent stand. Compare strip cutting.

pyrolysis--The breakdown of chemicals at high temperatures. Hydrocarbons pyrolyze in the absence of oxygen to simpler hydrocarbons, hydrogen, and carbon.

rainout--The removal of airborne particulates and gases by within-cloud processes followed by precipitation from the cloud. These include formation of droplets or ice crystals on the particulate acting as precipitation nuclei, dissolving of soluble gases into cloud and precipitation particles, and adhesion following collision with cloud particles. Different from washout below the cloud.

rate-of-spread--The relative activity of a fire in extending its horizontal dimensions. It may be expressed as rate of increase of the perimeter, as a rate of forward spread of the fire front, or as a rate of increase in area.

regeneration cutting--Any cutting intended to encourage or facilitate tree regeneration.

release--Freeing a tree or group of trees from competition by cutting or otherwise eliminating growth that is overtopping or closely surrounding.

residence time--The time an emission component is in the air between emission and removal from the air or change into another chemical configuration.

residue--See forest residue.

residue treatment--Manner of managing, manipulating, removing, or modifying forest residue. Treatments may involve piling, chipping, crushing, burning, burying, lopping, herbicide spraying of live residues, leaving for natural deterioration, or a combination of these.

resin--See natural resins.

resistance to control--The relative difficulty of constructing and holding a control line as affected by fire behavior and difficulty of line construction.

rhizomorph--A thick strand of fungal hyphae in which the individual hyphae have lost their identity, the whole mass behaving as an organized entity. The structure of the growing tip resembles that of a root tip; thus the name.

rhizosphere--The microenvironment of roots. Also called rooting zone.

riparian vegetation--Growing in close proximity to a watercourse, lake, swamp, or spring, and often dependent on its roots reaching the water table.

risk--The chance of a fire starting as determined by the presence and activity of causative agents.

rotation--The planned number of years between the formation or regeneration of a crop or stand and its final cutting at a specified stage of maturity.

running fire--A fire spreading rapidly, with a well-defined head. Compare backing fire, head fire, crown fire.

salvage logging--Removal of dead, dying, or deteriorating timber before it becomes worthless.

sanitation cutting--Removal of dead, damaged, or susceptible trees to prevent the spread of insects or disease.

sapling--A loose term for a young tree no longer a seedling but not yet a pole. Live trees 1 to 5 inches (2.54 to 12.7 cm) d.b.h.

saprophyte--A plant which utilizes dead organic material as food.

sap rot--Any rot characteristically confined to the sapwood.

sapwood--The outer layers of wood which, in the growing tree, contain living cells and stored food such as starch.

scalping--In tree planting, removal of sod or other vegetation to reduce competition with the seedling.

scarification--Loosening the top soil of open areas, or breaking up the forest floor, in preparation for regenerating by direct seeding or natural seedfall. Done to reduce vegetative competition and to expose mineral soil.

sclerophyll--Plant with thick, hard, heavily cutinized, evergreen leaves.

scorchline--Average height of foliage browning caused by a fire.

secondary succession--A successional stage of a plant community after the whole or part of the original vegetation has been supplanted. Compare succession.

seed tree cutting method--The mature timber is removed in one cut except for a small number of trees left singly or in small groups for the purpose of reseeding the cut area.

selection system (also, selection cutting)--1) *Individual* (single) tree selection - An uneven-aged silvicultural system in which trees are removed singly and periodically throughout the stand, leading to the formation of a mixture of age and size classes by individual trees. 2) Group selection - A modification of the selection system in which trees are removed periodically in small groups resulting in openings that do not exceed an acre or two (½ to 1 ha) in size. This leads to the formation of a mosaic of age class groups in the same forest.

sensible heat--Thermal energy resulting in a change of temperature.

seral--Relating to a successional stage in a plant community. Compare succession.

severe burn--Degree of burn in which all organic material is burned from the soil surface which is discolored by heat, usually to red. Organic matter below the surface is consumed or charred. Compare light burn, moderate burn.

shelterwood system--An even-aged harvest and regeneration system in which a new stand is established under a partial canopy of trees. The old stand is removed in a series of two or more harvest cuts, the last of which removes the shelterwood when the new even-aged stand is well established. Cuttings under this system are designated: *Preparatory* - to remove undesirable trees, prepare seed bed, and encourage seed production. *Seed* - to open stand to provide light and heat for seedlings. *Removal* - to gradually remove the remaining mature stand.

silting--Deposition of waterborne sediments in stream channels, lakes, reservoirs, or on flood plains.

silvicide--Herbicide used to kill or inhibit growth of woody plants, especially trees.

silvicultural system--A series of operations whereby a forest is tended, harvested, and regenerated. The actual procedures vary with forest type, species characteristics, product needs, environmental requirements, and uses of the forest. Classification is by type of harvest cutting. Compare clearcutting, seed tree cutting method, selection system, shelterwood system.

sink--In atmospheric chemistry, the receptor for material when it disappears or is removed from the atmosphere.

site--An area considered in terms of the type and quality of the vegetation the area can carry as indicated by its biotic, climatic, and soil conditions.

site index (also, site class)--A measure of site quality based on the height of the dominant trees at an arbitrarily chosen age.

site preparation--Removal or killing of unwanted vegetation, residue, etc., by use of fire, herbicides, or mechanical treatments in preparation for reforestation and future management. Compare type conversion.

site quality--A term denoting the relative productivity of a site for a particular tree species.

skidding--Moving logs by dragging or sliding, from stump to roadside, deck, or landing; similar to yarding in which logs may or may not be in contact with the ground.

skid trail--Any road or trail formed by the process of skidding logs from stump to landing.

skyline logging--A cable aerial logging system with which logs are suspended free of the ground from a carriage that rides on an overhead cable. Compare cable logging, balloon logging, high-lead logging.

slash--A complex of woody forest debris left on the ground after logging, land clearing, thinning, pruning, brush removal, or natural processes such as ice or snow breakage, wind, and fire. Slash includes logs, chunks, bark, branches, tops, uprooted stumps and trees, intermixed understory vegetation, and other fuels.

slash disposal--Treatment of slash to reduce the fire hazard or for other purposes. Compare residue treatment.

smoke episode--A period when smoke is dense enough to be an unmistakable nuisance.

smoke management--A system whereby current and predicted weather information pertinent to fire behavior, smoke convection, and smoke plume movement and dispersal is used as a basis for scheduling the location, amount, and timing of burning operations so as to minimize total smoke production and assure that smoke does not contribute significantly to air pollution.

smoke-sensitive area--An area in which smoke from outside sources is intolerable, owing to heavy population, existing air pollution, or intensive recreation or tourist use.

smoldering combustion--Combustion of a solid fuel, generally with incandescence and smoke but without flame. Compare glowing combustion.

snag--A standing dead tree or standing portion from which at least the leaves and smaller branches have fallen. Often called a stub if less than 20 feet tall (6.1 m).

soil bulk density--The mass of dry soil per unit bulk volume. The bulk volume is determined before drying to constant weight at 105° C (221° F).

soil compaction--The packing together of soil particles by surface pressure exerted by heavy equipment, tree felling, yarding, etc., resulting in an increase in soil density through a decrease in pore space.

soil-formation factors--The variable, usually interrelated natural factors that are active in and responsible for the formation of soil including parent rock, climate, organisms, topography, and time.

soil horizon--A layer of soil or soil material approximately parallel to the land surface, with well-defined physical, chemical, and biological properties or characteristics such as color, structure, texture, consistency, kinds and numbers of organisms present, degree of acidity or alkalinity, etc.

soil organic matter--The organic fraction of the soil; includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population.

soil permeability--The ease with which gases, liquid, or plant roots penetrate or pass through a bulk mass or layer of soil.

soil porosity--The volume percentage of the total bulk not occupied by solid particles.

soil water tension--See moisture tension.

sporophore--Any fungal structure which bears spores. May range from the inconspicuous black structures of a foliage disease to an edible mushroom or a conk on the side of a tree.

spotting--Behavior of a fire producing sparks or embers that are carried by the wind and start new fires beyond the zone of direct ignition by the main fire. Compare head fire.

stagnation--Condition of a forest stand wherein an overstocked stand ceases to grow, becomes weakened and susceptible to insect attack, and begins to generally deteriorate. Compare suppressed.

stand density--Density of stocking expressed in number of trees, basal area, volume, or other criteria on a per-acre basis.

stocking--The degree of occupancy of land by trees, measured by basal area and/or number of trees by size or age and spacing, compared to a similar measure of a stand fully utilizing the land's growth potential.

strip burning--Burning by means of strip firing, or burning narrow strips of fuel and leaving the rest of an area untreated by fire.

strip cutting--Removal of trees in strips. May be applied to clearcutting or partial cutting such as shelterwood or thinning.

subclimax--The seral stage in plant succession immediately preceding climax. Compare succession.

subsidence--Descending motion of air in the atmosphere taking place over an extensive area; characterized by comparatively warm temperature and low humidity due to warming by compression.

substrate--The substance, base, or nutrient on which an organism grows. Also compounds or substances that are acted upon by enzymes or catalysts and changed to other compounds in the chemical reaction.

succession--The gradual supplanting of one community of plants by another, the sequence of communities being termed a sere and each stage seral or successional.

suppressed--Crown class of trees that have been completely overtopped by the general crown cover and are in a weakened condition. Compare **stagnation**.

surface fire--Fire that burns surface litter, other loose debris of the forest floor, and small vegetation.

swamper burning--See progressive burning.

synergism--cooperative action of two or more chemicals so that their total effect is greater than the sum of their individual effects on the same organism.

terpenes--A group of hydrocarbons found in essential oils of many wood species and generally having a fragrent odor.

thermal admittance--A measure of the sensitivity of materials to temperature change. Equal to the square root of the product of density, specific heat, and thermal conductivity.

thinning--Cutting in an immature stand to increase rate of growth, improve stand composition, achieve broader spacing, and so recover material that would otherwise be lost. Compare release, precommercial thinning, partial cutting.

thinning slash--See slash and forest residue.

timelag--The time interval in which a particular kind and size of dead fuel loses approximately two-thirds (63 percent) of the difference between its initial moisture content and its equilibriun moisture content under standard drying conditions of 20-percent relative humidity and 80' F (26.67' C). Timelags for ponderosa pine sapwood dowels are:

less than 1/4-inch diameter		1 hour
1/4- to 1-inch diameter	(0.6- to 2.5-cm)	10 hours
1- to 3-inch diameter	(2.5- to 7.6-cm)	100 hours
6-inch diameter	(15.2-cm)	1,000 hours

tractor logging--Yarding of logs from stump to loading point by wheeled or crawler tractor as differentiated from horse logging, cable logging, and helicopter logging. Compare aerial logging, skidding.

transpiration--The process by which water vapor passes from the foliage or other parts of a living plant to the atmosphere.

troposphere--That portion of the atmosphere from the earth's surface to the tropopause; that is, the lowest 10 to 20 km (33,000 to 66,000 ft) of the atmosphere. The troposphere is characterized by decreasing temperature with height, appreciable vertical wind motion, appreciable water vapor content, and weather.

type conversion--The conversion from a less desirable vegetative type to a more desirable type; e.g., from brush to coniferous forest, or from a decadent old forest to a managed plantation. Compare site preparation.

understory--Generally, those trees and woody species growing below an overstory.

uneven-aged--A class of forest or stand in which trees or groups of trees that differ markedly in age are intermingled.

unstable air--Air in which vertical currents, when started, will continue and intensify. Evidenced by cumulus clouds, turbulence, gusty winds, and dust devils. Caused by a decrease of temperature with height greater than adiabatic; i.e., greater than 5.4° F per 1,000-foot elevation (9.8° C per km) in dry air. Compare inversion.

vector--An organism, usually an insect, which carries and transmits disease or decay-causing micro-organisms.

view--Relative proportion of earth and sky seen from a point. Important in determining the radiational temperature characteristics of the point.

washout--The sweeping out of airborne particulates by collision with precipitation, predominantly below the cloud base. Compare rainout.

water bar--A shallow channel, or raised barrier; e.g., a ridge of packed earth or a thin pole laid diagonally across the surface of a road or trail so as to lead off water, particularly storm water.

weed tree--Any tree of a species having little value and occupying space needed for more desirable species.

white rot--Any wood rot that attacks both the cellulose and lignin, producing a generally whitish residue that may be spongy or stringy, or occur in pockets; e.g., Fomes *annosus*. Compare brown rot.

whole tree logging--Felling and transporting the whole tree without the stump, but with its crown, for trimming and bucking at a landing or mill.

wildfire--An unplanned fire that is not being used as a tool in forest protection or management in accordance with an authorized permit or plan and which requires suppression.

witches' broom--An abnormal, proliferated, compacted, brushlike growth often found in forest trees as caused by dwarf mistletoe.

yarding--Moving of logs from stump to roadside deck or landing. Compare skidding.

YUM (yarding unutilized material)--Logging requirement whereby woody material of a specified minimum size is removed from a,cutting area and piled. After piling it is available for salvage or burning.

METRIC CONVERSION FACTORS

U.S. to Metric	Metric to U.S.
Distance	
1 in = 2.54 cm	1 cm = 0.3937 in
1 ft = 0.304 8 m	1 m = 39.37 in
1 mi = 1.609 344 km	1 m = 3.28084 ft
	1 km = 0.6214 mi
Area	
1 ft^2 = 0.092 9 m^2	1 m^2 = 10.76 ft^2
1 acre = 0.404 685 6 ha	1 ha = 2.4710538 acres
Weight	
1 lb = 0.453 592 kg	1 kg = 2.2046226 lb
1 short ton (2,000 lb) = 0.907 2 metric ton	1 metric ton (1 000 kg) = 2,204.6226 lb
	1 metric ton = 1.1023 ton
Volume	
1 ft^3 = 28.316 8 dm^3 = 28.316 8 liters	1 liter = 1.0567 qt
1 ft^3 = 0.028 316 8 m^3	1 m^3 = 35.3147 ft^3
Liquid	
1 qt = 0.946 352 9 liter	1 liter = 1.0567 qt = 0.2642 gal
1 gal = 0.003 785 m^3 = 3.785 liters	1 m^3 = 264.2 gal
Density	
1 lb/ft^3 = 0.016 018 5 g/cm^3	1 g/cm^3 = 62.428 lb/ft^3
Temperature	
1° Fahrenheit = 5/9° Celsius	1° C = 1.8° F
COMBINATIONS:	
Speed	
1 mi/h = 1.609 344 km/h = 0.447 04 m/sec	1 m/sec = 2.23694 mi/h
Volume/area	
1 ft^3/acre = 0.069 97 m^3/ha	1 m^3/ha = 14.29 ft^3/acre

1/ Robert J. List. Smithsonian meteorological tables. Smithsonian Miscellaneous Collections, Volume 114, 527 **p.** Smithsonian Institute, Washington, D.C. 1951.

2/ Robert C. Weast. Handbook of chemistry and physics. The Chemical Rubber Co., Cleveland, Ohio. 1972.

Weight/area

1 lb/acre = 1.120 85 kg/ha
1 ton/acre = 2.241 7 metric tons/ha

1 kg/ha = 0.89218 lb/acre
1 metric ton/ha = 0.4460896 ton/acre

Liquid/area

1 gal/ft^2 = 40.744 7 liters/m^2

1 liter/m^2 = 0.02454 gal/ft^2

Energy/weight

1 Btu/lb = 0.555 555 cal/g

1 cal/g = 1.8 Btu/lb

Pressure - standard atmosphere

14.696 lb/in^2 = 1.013 25 bar
29.29 in mercury = 760 mm mercury

☆GPO # 697452

The mission of the PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION is to provide the knowledge, technology, and alternatives for present and future protection, management, and use of forest, range, and related environments.

Within this overall mission, the Station conducts and stimulates research to facilitate and to accelerate progress toward the following goals:

1. Providing safe and efficient technology for inventory, protection, and use of resources.
2. Development and evaluation of alternative methods and levels of resource management.
3. Achievement of optimum sustained resource productivity consistent with maintaining a high quality forest environment.

The area of research encompasses Oregon, Washington, Alaska, and, in some cases, California, Hawaii, the Western States, and the Nation. Results of the research will be made available promptly. Project headquarters are at:

Fairbanks, Alaska	Portland, Oregon
Juneau, Alaska	Olympia, Washington
Bend, Oregon	Seattle, Washington
Corvallis, Oregon	Wenatchee, Washington
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