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FIRE EFFECTS GUIDE

Sponsored by:

National Wildlife Coordinating Group

Fire Use Working Team

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PREFACE

by Dr. Bob Clark and Melanie Miller

A. Purpose

The Federal government manages a variety of ecosystems across the United States, including deserts, grasslands, tundra, shrublands, forestlands, estuaries, and riparian zones. These ecosystems range from arid to humid, warm to cold, and sea level to over 10,000 feet elevation. Fires naturally occur in almost all of these ecosystems, with fire characteristics determined by climate, vegetation, and terrain.

The purposes of this Guide are to summarize available information on fire effects principles and processes, provide references for additional information, and provide guidelines for the collection, analysis, and evaluation of wild and prescribed fire effects data. Basic mechanisms of fire effects are described so that the reader will be able to understand and interpret fire effects literature, and evaluate observed results that conflict with those presented in published reports. The goal is to improve fire management by improving our ability to manage fire effects.

The Guide was written as an aid for resource managers and fire managers. It can be used for managing and evaluating wildfires; developing and implementing emergency fire rehabilitation plans; planning, monitoring, and evaluating prescribed fires; developing activity plans such as timber management plans, allotment management plans, and threatened and endangered species recovery plans; and providing fire management input for land use plans.

B. Assumptions

Ecosystems have evolved with, and adapted to, specific fire regimes. In a particular ecosystem, natural fires occurred with fairly specific, albeit irregular, frequency and typical season of occurrence; with characteristic fireline intensity and severity; and characteristically did or did not involve the crowns of trees or shrubs. Gross differences occurred among ecosystems. For example, frequent, low intensity, surface fires were common in ponderosa pine ecosystems, whereas fires in big sagebrush were probably less frequent, of higher intensity, and killed much of the sagebrush overstory. High intensity, stand replacement fires at long intervals were characteristic of some forest types, while annual fires may have been common on some Great Plains grasslands. Despite this variability in fire regimes, universal principles and processes govern response of ecosystem components to fire. Recognition and understanding of the principles and processes can help our understanding of the variability in postfire effects that is often reported in the literature, and differences between reported results and local observations on burned areas. This knowledge will enable resource and fire managers to predict and evaluate fire effects, regardless of ecosystem or fire regime.

Fire effects are the result of an interaction between the heat regime created by the fire and the properties of ecosystem components present on the site. For example, plant species in vegetation types that have evolved with frequent fire tend to be much more resistant to fire than species from plant communities that rarely burned. The effects of a fire burning under the same conditions may be very different on soils of different textures or chemical properties. Variation in fire effects may also occur within ecosystems because of differences in site characteristics, fuel conditions, and weather prior to, during, and after the fire. A fire may have different effects upon the same site if it occurs in different seasons or within the same season but with different fuel, duff, and soil moisture. For these reasons, it is important to document conditions under which the fire occurred, and the characteristics of the fire, as part of any effort to monitor postfire effects.

The words fire intensity, severity, fireline intensity, and burn severity are often used interchangeably in the literature. The following terminology is used throughout this Handbook to describe the properties of fire. All definitions that describe the behavior of a flaming fire are those used in the Fire Behavior Prediction System (Rothermel 1983), including fireline intensity, the rate of heat release per linear foot of the flaming front. Burn severity is a qualitative assessment of the heat pulse toward the ground, and relates to subsurface heating, large fuel and duff consumption, and consumption of litter and organic layers beneath isolated trees and shrubs. The terms fire intensity and intensity are used by some authors to describe the overall heat regime of a fire. They are generic terms that are often confused with fireline intensity, and are not used as a synonym for fireline intensity in this Handbook.

The Guide recognizes that a natural fire regime cannot be perpetuated in unnatural communities. Timber harvest practices, grazing patterns and degree of use, the accidental or deliberate introduction of exotic plants and animals, other cultural activities that alter fuel continuity and loading, and the modification of historic fire patterns through active suppression have changed many plant communities. Interruption of fuel continuity by livestock grazing, road construction, and other developments has resulted in fires that are less frequent, smaller, and of lower fireline intensity, in some ecosystems. The introduction of exotic plants such as cheatgrass, coupled with anthropogenic ignition sources, has greatly increased fire size and frequency in other ecosystems.

Active suppression has resulted in large areas, especially in shrublands and forests, that are extremely susceptible to fire. The exclusion of fire has resulted in a larger proportion of vegetation in older age classes, except in regulated forests, which are more susceptible to insect and disease infestations. The amount of dead plant material has increased, either accumulated on the ground or retained on plants. In plant communities with historically short fire cycles, the absence of fire has allowed the development of fuel ladders between the surface and the overstory. Fires which do occur are often carried into the tree crowns by large accumulations of down dead woody fuels or understory trees, causing a stand replacement fire in forest types where historically, overstory trees were rarely killed. In vegetation communities with long natural fire cycles, younger, intermixed, less flammable age classes of vegetation are not as prevalent as they would have been under a natural fire regime. Coupled with the increased incidence of insect and disease, the continuity of highly flammable stands has increased, resulting in greater potential for extremely large fires. Plans for the

C. Handbook Organization

The chapters of this Guide discuss different elements that relate to our management of fire effects and specific responses of different ecosystem components to fire. This Handbook recognizes that separate discussions of fire effects on fuels, soils, watershed, plants, and wildlife are artificial, because fire effects are an integration of the responses of all of these components to fire. Despite the fact that fire effects occur holistically, ecosystem components are discussed individually as a means of organizing the information. Chapters describe basic principles and processes that regulate fire effects, including fire behavior and characteristics, fuels, air quality, soils and watershed, plants, wildlife, and cultural values. Considerations for management of fire effects on these resources, and a discussion of appropriate techniques for monitoring fire effects, are contained in each of these chapters. Monitoring is included in this Handbook because techniques that accurately describe long-term trends in plant community condition, for example, are not adequate to detect significant and sudden changes caused by burning. Because an understanding of prefire and postfire grazing management, data analysis, and documentation and evaluation procedures is critical to sound management and monitoring of fire effects, chapters on each of these topics are also included. Resource management is goal oriented. The first chapter in this Guide is a discussion of goals and objectives and how they fit into planning for the use and management of fire.

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CHAPTER I - DEVELOPMENT OF OBJECTIVES

By Dr. Tom Zimmerman

A. Introduction

Management is the process of anticipating the future, setting objectives, implementing an action, achieving an output, and performing an evaluation comparing the output to the objective. Management is not possible without setting objectives. Clear and easily communicated objectives facilitate the management process.

In land management programs, the desired outcome of management actions is expressed as management objectives. Objectives represent an important component of all land management programs and are the single most important factor driving all management actions.

B. Definitions and Qualities of Good Objectives

1. Goals and Objectives - Definition. In land management, both goals and objectives are important. Goals are primary and basic products of the long range management plans. These goals are commonly referred to as land use decisions. Goals are relatively short statements that discuss what the public lands are to be used for and where the uses will occur. Each statement addresses a land use, but is not limited to the principal or major use.

Objectives are a necessary component of the planning process; they provide a bridge between goals and the implementation phase. Objectives describe what procedures will be used and when actions will be completed.

During the planning of fire management projects, objectives are formulated and used as the basis for development of an action plan. Interdisciplinary (I.D.) teams coordinate various concerns and develop objectives for a project. The I.D. teams are composed of resource specialists from different disciplines who address concerns of the affected resources and resolve conflicts among resource disciplines that arise from specific management actions.

2. Qualities of Good Objectives. Fire management objectives must be made up of certain attributes or they will not convey the necessary guidance. Good objectives must be informative and **SMART**. Objectives that are **SMART** are:

S - Specific - what will be accomplished, using limiting factors, and identifying the range of acceptable change from the present to the proposed condition.

M - Measurable - the present and proposed condition must be quantifiable and measurable.

A - Achievable - can be achieved within a designated time period.

R - Related/Relevant - related in all instances to the land use plan goals and relevant to current fire management practices.

T - Trackable - objectives must be trackable over time and must include a definite timeframe for achievement, monitoring, and evaluation.

3. Kinds of Objectives.

a. Land use decisions (goals). These are broad statements, usually specified in land management plans, that deal with large areas over long time periods (e.g., 10 years). Land use decisions establish resource condition objectives; the allowable, limited, or excluded uses for an area (land use allocations) and the terms and conditions for such use; and management actions that will be taken to accomplish multiple use goals.

b. Resource management objectives. Resource management objectives identify the changes in water, soil, air, or vegetation from the present to proposed conditions. Resource objectives can also describe an existing resource condition that should be maintained.

c. Treatment objectives. These are very well-defined statements that describe what a treatment must accomplish in order to meet a stated resource management objective. This type of objective is site-specific and must utilize the **SMART** concept.

Any statement that is an objective **must** identify the change from present conditions to the proposed conditions (the changes that are planned) and the limiting factors.

C. How Objectives Relate to Project Inventory, Development, Implementation, Monitoring, and Evaluation

Objectives are an important part of management actions and are prerequisite to sound land and resource management. Objectives not only drive the planning system, they also drive the full spectrum of project implementation, monitoring, and evaluation.

During the fire planning process, for example, the planner uses resource management objectives (standards) as guidance to determine what fire management responses and activities are necessary. These standards then provide guidance in determining what and how much information should be collected prior to and during project implementation. At this point, knowledge of fire effects becomes a necessary part of the planning process. Fire effects information helps to determine what will be done, how many resources are needed, how much funding the fire program will need, and what should be evaluated to ensure efficient accomplishment of the workload.

D. Relationships of Different Tiers (Levels) of Planning to Objectives

Generally, objectives start as issues when the land use planning process is initiated. (Issues are usually conflicts between two or more resource uses or demands that must be resolved in the plan.) Issues are generally defined in terms of the desired state of achievement for environmental values and socioeconomic conditions affected by management activities and resource decisions. The next step is development of alternatives that include a range of ways to resolve the issues. After the preferred alternative is selected, local guidance for resource functions is developed that contains resource management objectives.

Land use planning systems used by most federal agencies are divided into five distinct tiers: national, geographically defined management areas, individual resource functions, and strategic and tactical site specific implementation (Table I-1). National policy is established in public laws, federal regulations, Executive Orders, and other Presidential, Secretarial, and Director approved documents. Policy guidance for planning is developed, as needed, through interpretation of national policy, public participation activities, and from coordination and consultation with other federal agencies.

Table I-1: Relationship of Planning Tiers to Fire Management Objectives, Products and Fire Effects Applications

Planning Tier	Type of Objectives	Product	Fire Effects Applications
National		Policy and Regulations	National policies and guidance regarding fire presence and exclusion in wildland ecosystems
Geographically defined management area	Land use decisions	Resource Management Plan (BLM, NPS) Comprehensive Conservation Plan (FWS) Integrated Resource Management Plan (BIA) Forest Land Management Plan (FS)	Integration of fire and resource management within a geographically defined management area

Local guidance for individual resource components	Resource management objectives	Habitat Management Plan Compartment Plan Allotment Plan	The role of fire in resource management within a specific administrative unit.
Strategic site specific implementation	Strategic program objectives	Fire Management Activity Plans Fire Management Plan Fire Management Action Plan Wilderness Fire Management Plan	Identification of appropriate allocation of fire suppression, fire use and fuels management activities necessary to achieve resource management objectives
Tactical site specific implementation	Treatment objectives	Prevention Plan Presuppression Plan Escaped Fire Situation Analysis Postfire Rehabilitation Plan Prescribed Fire Plan Other	Interpretation and analysis of site specific fire effects to guide development and implementation of a program of action to accomplish treatment objectives

Resource management plans developed for geographically defined management areas establish the combinations of land and resource uses; related levels of investment, production, and/or protection to be maintained; and general management practices and constraints for various public land resources. These are set forth as the terms, conditions, and decisions that apply to management activities and operations and are presented in the form of multiple-use prescriptions and plan elements.

The third planning tier, developed at a local level, provide guidance for individual resource functions. At this level the role of fire is discussed, and how fire can be used or is detrimental in achieving the individual resource objectives.

Site specific stratigic and tactical implementation plans are the final step in the fire planning process. The primary role of these plans is to identify operational guidance to accomplish site specific treatment objectives. To continue with the example of the fire management component, Fire Management Activity Plans delineate areas to receive different levels of fire suppression, fire use, and fuels treatment. Resource management objectives developed at this level are derived directly from land use decisions. Prescribed fire plans refer to resource management objectives developed in activity plans and identify treatment objectives. Resource management objectives referenced in prescribed fire plans describe second order fire effects, the indirect effects of fire treatment that occur over the longer term, such as increased plant productivity, changes in species composition, or increased off-site water yield. Fire treatment objectives are developed from the resource management objectives and state exactly what immediate effects the fire must create in order to achieve the resource objectives. Fire treatment objectives describe first order fire effects such as plant mortality, fuel reduction, or duff consumption. An example of a fire treatment objective is: to remove 90 percent of existing sagebrush crown cover, using fireline intensities that consume sagebrush crowns, leaving residual stems that are six inches or less in height.

E. Summary

Land management programs are objective driven. Objectives must be based on an amount of information sufficient to determine if a change from the present condition to the proposed condition can be achieved. Establishing objectives is a task of major importance and deserves an allotment of sufficient attention and time. Both objectives and fire effects information become more precise as site specificity increases.

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CHAPTER II - FIRE BEHAVIOR AND CHARACTERISTICS

by Melanie Miller

A. Introduction

Frequently a fire is described as hot or cool, high or low intensity, or flaming or smoldering. Too often fire behavior and characteristics are not described at all. Standard terminology exists for describing the behavior, characteristics, and heat regime of wildland fires. Monitoring and documentation of fire behavior and characteristics according to these standard terms can increase understanding of the relationship between the effects created by a specific fire and that fire's heat regime, and make comparisons among different fires possible.

The behavior of the flaming front of a surface fire can be predicted with fire behavior technology. Other characteristics of the surface fire, such as duration of all phases of combustion and penetration of heat into duff and soil layers cannot be predicted with existing models. The rate of heat release and growth of crown fires can be estimated. It is important to understand some of the different properties a wildland fire can have, how they can be described, which can be predicted, and how the various aspects of a fire's heat regime can be related to the fire treatment.

This chapter contains a brief overview of principles of fire behavior and characteristics. More detailed information can be obtained from formal courses in fire behavior and in courses that are prerequisites for certain prescribed fire positions. The chemistry and phases of the combustion process are described in the Air Quality chapter of this Guide, Chapter IV.B.1. The effect of fuel moisture on fire behavior is described in this chapter, but factors affecting fuel moisture content and fuel consumption are discussed in Chapter III.B, this Guide.

B. Principles and Processes

1. The Fire Environment. Wildland fire is influenced by three interacting classes of variables: fuels, topography, and air mass (Countryman 1972).

a. Fuels. Wildland fuels provide the energy source for fire. Fuels consist of both living and dead vegetation, the latter in various stages of decay. Fuels occur in three fairly distinct strata: ground, surface, and aerial. A fire can burn in one, two, or all three strata at once, or change the layer in which it is burning as fuels and environmental conditions change throughout an area. Fuels are discussed in greater detail in Chapter III. B.1., this Guide.

(1) Ground fuels. Ground fuels are all combustible materials below the surface litter layer. These fuels may be partially decomposed, such as forest soil organic layers (duff), dead moss and lichen layers, punky wood, and deep organic layers (peat), or may be living plant material, such as tree and shrub roots.

(2) Surface fuels. Surface fuels are those on the surface of the ground, consisting of leaf and needle litter, dead branch material, downed logs, bark, tree cones, and low stature living plants.

(3) Aerial fuels. Aerial fuels are the strata that is above the surface fuels and include all parts of tree and tall shrub crowns. The aerial fuel layer consists of needles, leaves, twigs, branches, stems, and bark, and living and dead plants that occur in the crowns such as vines, moss, and lichens.

(4) Ladder fuels. Ladder fuels bridge the gap between surface and aerial fuels. Fuels such as tall conifer reproduction can carry a fire from the surface fuel layer into tree crowns.

b. Topography. Topography includes slope, aspect, elevation, and how these elements are configured. Topography can change suddenly, particularly in mountainous terrain, and its influence on fire behavior can rapidly change as well.

(1) Direct effect.

(a) Slope is an extremely important factor in fire behavior because the flames of a fire burning upslope are positioned closer to the fuels ahead of the fire. This dries and preheats the fuels at a greater rate than if they were on flat terrain.

(b) Topography channels wind and can create turbulence and eddies that affect fire behavior. Topography also affects diurnal air movement, influencing the velocity of day time upslope and night time downslope winds.

(2) Indirect effect.

(a) The combined effects of aspect and elevation create different microclimates that affect vegetation distribution and hence fuel type.

(b) Fuel moisture can vary with aspect, elevation, and vegetation type. This is discussed further in Chapter III.B.4, this Handbook.

c. Air mass. Weather components such as temperature, relative humidity, windspeed and direction, cloud cover, precipitation amount and duration, and atmospheric stability are all elements of the air mass. These values can change quickly over time, and significantly with differences in aspect and elevation. The air mass affects fire both by regulating the moisture content of fuel (discussed in Chapter III.B.4.), and by its direct effect on the rate of combustion. The following is a brief discussion of the effect of air mass factors on fire behavior and characteristics.

(1) Temperature. Atmospheric temperature affects fuel temperature. The ease of ignition, the amount of heating required to raise fuel to ignition temperature (320 C.; 608 F.) (Burgan and Rothermel 1984), depends on initial fuel temperature. The most important effect of temperature, however, is its effect on relative humidity and hence on dead fuel moisture content. (See Chapter III.B.4.).

(2) Windspeed. Wind has a significant effect on fire spread. It provides oxygen to the fuel and, combined with slope, determines which way the fire moves. Wind tips the flame forward and causes direct flame contact with fuel ahead of the fire (Burgan and Rothermel 1984). These fuels are preheated and dried by this increased transfer of radiant and convective heat. Windspeed has the most influence on fire behavior in fuel types with a lot of fine fuels, such as grasslands.

2. Combustion Process.

a. Two stage process. Within a wildland fire, the processes of pyrolysis and combustion occur simultaneously (Ryan and McMahon 1976 in Sandberg et al. 1978).

(1) Pyrolysis. When first heated, fuels produce water vapor and mostly noncombustible gases (Countryman 1976). Further heating initiates pyrolysis, the process by which heat causes chemical decomposition of fuel materials, yielding organic vapors and charcoal (ibid.). At about 400F. (204 C)., significant amounts of combustible gases are generated. Also at this temperature, chemical reactions start to produce heat, causing pyrolysis to be self-sustaining if heat loss from the fuel is small. Peak production of combustible products occurs at when the fuels are about 600 F. (316 C.) (ibid.).

(2) Combustion. Combustion is the process during which combustible gases and charcoal combine with oxygen and release energy that was stored in the fuel (Countryman 1976) as heat and light.

b. Phases of combustion. The following summary is derived from Ryan and McMahon (1976 in Sandberg et al. 1978), except where noted. For a more complete discussion of the phases of combustion, see Sandberg et al. (1978).

(1) Pre-ignition phase. In this phase, heat from an ignition source or the flaming front heats adjacent fuel elements. Water evaporates from fuels and the process of pyrolysis occurs, the heat-induced decomposition of organic compounds in fuels.

(2) Flaming phase. Combustible gases and vapors resulting from pyrolysis rise above the fuels and mix with oxygen. Flaming occurs if they are heated to the ignition point of 800 to 900F. (427 to 482 C.), or if they come into contact with something hot enough to ignite them, such as flames from the fire front (Countryman 1976). The heat from the flaming reaction accelerates the rate of pyrolysis. This causes the release of greater quantities of combustible gases, which also oxidize, causing increased amounts of flaming (Ryan and McMahon 1976 in Sandberg et al. 1978).

(3) Glowing phase. When a fire reaches the glowing phase, most of the volatile gases have been driven off. Oxygen comes into direct contact with the surface of the charred fuel. As the fuel oxidizes, it burns with a characteristic glow. This process continues until the temperature drops so low that combustion can no longer occur, or until all combustible materials are gone.

(4) Smoldering phase. Smoldering is a very smoky process occurring after the active flaming front has passed. Combustible gases are still being released by the process of pyrolysis, but the rate of release and the temperatures maintained are not high enough to maintain flaming combustion. Smoldering generally occurs in fuel beds with fine packed fuels and limited oxygen flow such as duff and punky wood. An ash layer on these fuel beds and on woody fuels can promote smoldering by separating the reaction zone from atmospheric oxygen (Hartford 1993).

3. Fire Behavior Prediction. The Fire Behavior Prediction System is a collection of mathematical models that were primarily developed to predict the behavior of wildland fires (Rothermel 1983). The models include those used to forecast behavior, area and perimeter growth of a surface fire; models that estimate spot fire potential, crowning potential, and crown fire behavior; and fire effects models that predict tree crown scorch height and tree mortality.

Solutions for most of these models can be obtained from nomograms (Albini 1976) and the BEHAVE system. BEHAVE is a set of programs for use on personal computers (Andrews 1986; Andrews and Chase 1989; Burgan and Rothermel 1984). More information about the BEHAVE system is contained in Chapter XII.C.1, this Guide.

4. Fire Spread Model. A fire spread model was developed by Rothermel in 1972 that allows managers trained in the use of the model to make quantitative estimates of fire behavior. The model is a mathematical representation of fire behavior in uniform wildland fuels. The fire spread model describes the processes that control the combustion rate: moisture evaporation, heat transfer into the fuel, and combustible gas evolution (Rothermel 1972).

a. Assumptions. Basic assumptions of the fire spread model are (Rothermel 1983):

(1) The fire is burning in a steady state in homogeneous surface fuels, not in crown or ground fuels.

(2) The percent slope and aspect are uniform.

(3) The wind is constant in both velocity and direction.

(4) The model describes fire behavior within the flaming front. The model does not describe behavior after the fire front has passed, such as during fuel burnout.

(5) The behavior of the fire is no longer influenced by the source of ignition or by suppression activities.

These assumptions are often violated when prescribed burning because ignition is often used to manipulate the fire. A common objective for burning is to consume fine fuels before the fire reaches a steady state. The predicted values do provide an estimate of fire behavior if a prescribed fire escapes.

b. Inputs to the Fire Spread Model. Required inputs to the fire spread model include fuel model, fuel moisture content, slope, and wind.

(1) Fuel model. A fuel model is a mathematical representation of the amount and kind of fuels present. The Fire Behavior Prediction System provides 13 standard fuel models that describe the characteristics of the portions of the fuel complex carrying the fire. Custom fuel models more closely describing a specific fuel situation also can be developed using the BEHAVE program (Burgan and Rothermel 1984). (See XII. C.1.a., this Guide.)

(a) Categories. In most situations, the flaming front of a fire advances through fine fuels such as grass, shrub foliage, litter, and small diameter down dead woody fuels. Wildland fuels can be grouped into four categories, according to the nature of the carrier fuels.

i. Grass or grass dominated: the primary carrier of the fire is grass.

ii. Shrub dominated: the primary carrier of the fire is either shrubs or litter beneath shrubs.

iii. Timber litter dominated: the primary carrier of the fire is litter beneath a timber (tree) stand.

iv. Logging slash: the primary carrier of the fire is residual material left from logging operations.

(b) Fuel properties. Fuel particles within a fuel complex have physical properties that influence the way they burn. The 13 standard fire behavior fuel models have specified physical properties (Anderson 1982). Properties can be changed to create a custom fuel model that may better describe a particular fuel complex. (See XII.C.1.a., this Guide.) Fuel properties that are the most important for determining the way a fire will behave include the following.

i. Fuel loading. The amount of live and dead fuel is expressed in weight per unit area. Loadings are grouped by particle size class and are usually expressed in tons per acre (kilograms per square meter). Total fuel is all plant material both living and dead present on a site. Available fuel is the amount of fuel that will burn under a specific set of fire conditions.

ii. Fuel size class. Dead fuels are divided into size classes based on diameter: less than 1/4-inch, 1/4 to 1-inch, 1 to 3 inches, and greater than 3 inches. (Metric equivalents of these size classes are: less than 0.6 centimeters, 0.6 to 2.5 centimeters, 2.5 to 7.6 centimeters, and greater than 7.6 centimeters.) Fuel size class is related to the rate at which particles wet and dry. This is discussed further in Chapter III.B.4., this Guide.

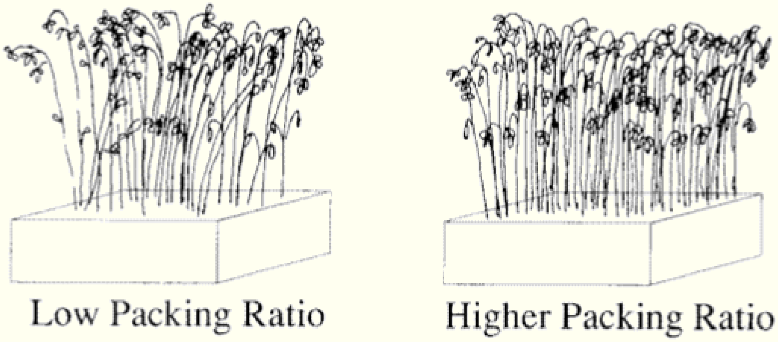
iii. Size class distribution. Fires usually start and spread in fine fuels, that is, those less than 1/4 inch in diameter. These fuels ignite increasingly larger size classes of fuels. If fine fuels or an intermediate size class are missing, a fire may not ignite or may not spread.

iv. Surface area to volume ratio. The surface area to volume ratio is a function of the particle size: the more finely divided the fuel material, the larger the ratio. Because small fuel particles have a large surface area compared to their volume, they dry out and ignite more rapidly than larger particles. Therefore, fine fuels usually have the most influence on fire behavior.

v. Fuel bed depth. Fuel bed depth is the depth of the surface fuel layer, i.e., the average height of surface fuels contained in the combustion zone of a spreading fire front.

vi. Packing ratio. The packing ratio is a measure of the compactness of the fuel bed. Expressed as a percentage, the packing ratio is the percentage of the fuel bed that is composed of fuel, the remainder being air space between the individual fuel particles (Burgan and Rothermel 1984). A fuel bed with no fuel has a packing ratio of zero, while a solid block of wood has a packing ratio of one (ibid.). A very open or porous fuel bed burns slowly because individual fuel particles are located so far apart that little heat is transferred among particles. A very compact fuel bed also burns slowly because airflow among the fuel particles is impeded, and there are large numbers of fuel particles that must be heated to ignition temperature. For every size of fuel particle, there is an optimum packing ratio at which heat transfer and oxygen produce the most efficient combustion (Burgan and Rothermel 1984). Compactness also influences the drying rate of fuel.

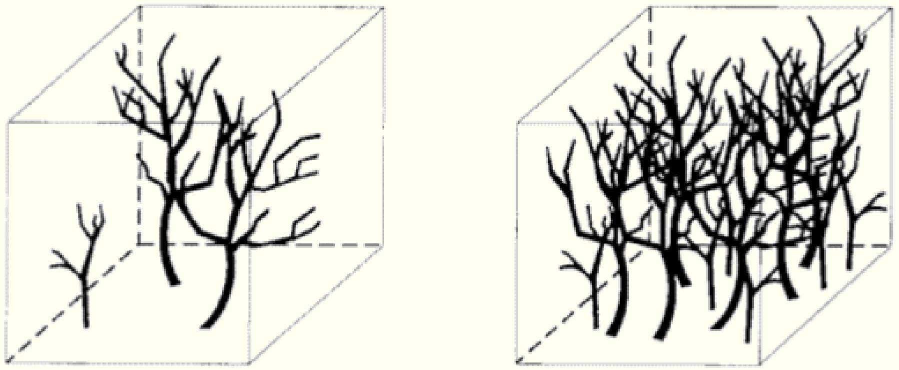
Packing ratio - percentage of the fuel bed volume that is composed of fuel.



Expressed as: ratio between 0 and 1.0.

vii. Bulk density. Bulk density is the actual fuel weight per unit. It is calculated by dividing the weight per unit area by the fuel bed depth. It is a measure of the oven dry weight of fuel per cubic foot of the fuel bed, usually expressed as pounds per cubic foot. The higher the bulk density of the fuel, the slower the spread rate, because more fuel must be preheated to ignition temperature in order for the fire to spread.

The actual weight of the fuel within a volume of a fuel bed.



Expressed as: pounds per cubic foot (lbs./ft^3), or
grams per cubic centimeter (g/cm^3).

viii. Fuel continuity. Fuel continuity is a description of the distribution of fuels. Fire spread is most likely in continuously distributed fuels. The greater the fuel discontinuity, the higher the fireline intensity required for fire spread. Fuel continuity is described in terms of both horizontal and vertical continuity. Horizontal continuity relates to the horizontal distances between fuel particles and relates to percent cover. The proximity of tree or shrub crowns affects the ease with which fire can spread in a live fuel strata. Vertical continuity describes the proximity of surface fuels to aerial fuels and affects the likelihood that a fire can move into the vegetative canopy.

ix. Heat content. The most important aspect of fuel chemistry influencing fire behavior is heat content. This value expresses the net amount of heat that would be given off if the material burns completely (or at 100 percent efficiency), rated as Btu per pound of fuel. The heat content for all species of dead woody fuel is essentially the same (Albini 1976). The presence of pitch in wood, and of volatile compounds such as oils and waxes in some live fuels, increases heat content, and thus flammability.

x. Live fuels. Some fuel types contain a significant component of live fuels in the surface fuel layer, including shrubs, grasses, and forbs. The importance of live fuels to fire behavior can change throughout the year. Their volume can increase significantly during greenup and the early part of the growing season. They can lose their foliage at the end of the growing season or during a drought. Seasonal fluctuations in moisture content occur that significantly affect flammability. The moisture cycles within live fuels are discussed in more detail in Chapter III.B.5., this Guide.

While technically live fuels, mosses and lichens do not have physiologically controlled seasonal moisture cycles. Their moisture content is very sensitive to changes in temperature and relative humidity and can become as low as that of surface litter layers. A dry surface layer of mosses and lichens can readily carry a fire in black spruce forests in Alaska (Dyrness and Norum 1983).

The volatile compounds in some species of live fuels allow them to burn at a higher moisture content than if there are few or no volatiles (Norum 1992). Sagebrush (*Artemisia* spp.) is considered to be a moderately volatile fuel, while chaparral shrubs, conifers, and dead juniper are highly volatile fuels (Wright and Bailey 1982).

Fire behavior in stands of shrubs containing volatile compounds can be extreme. This is attributed not only to their chemical content, but also to the high percentage of dead material that some of these stands of shrubs contain, and the ideal mixture of fuel to air within the shrub canopy (Burgan 1993).

(2) Fuel moisture. Fuel moisture content describes how wet or dry the fuels are. Moisture content is the single most important factor that determines how much of the total fuel is available for burning, and ultimately, how much is consumed. Fuel moisture determines if certain fuels will burn, how quickly and completely they will burn, and what phases of combustion the fuels will support. Fuels with a higher moisture content reduce the rate of energy release of a fire because moisture absorbs heat released during combustion, making less heat available to preheat fuel particles to ignition temperature (Burgan and Rothermel 1984). Ignition will not occur if the heat required to evaporate the moisture in the fuels is more than the amount available in the firebrand (Simard 1968). Environmental factors regulating dead fuel moisture content, and the relationship between fuel moisture content and fuel consumption, are discussed in III.B.4., this Guide.

(a) Fuel moisture formula. Fuel moisture content is the percent of the fuel weight represented by water, based on the dry weight of the fuel. In a word equation, it is:

Percent Moisture Content = Weight of Water / Oven-dry Weight of Fuel x 100

Moisture content can be greater than 100 percent because the water in a fuel particle may weigh considerably more than the dry fuel itself. For example, a green leaf may contain three times as much water as there is dry material, leading to a moisture content of 300 percent. Moisture content of duff and organic soil can be over 100 percent. Methods to measure and calculate fuel moisture content are described in Chapter III.D., this Guide.

(b) Moisture of extinction. The extinction moisture content is the level of fuel moisture at which a fire will not spread. It is a function of the fuel type and fuel bed geometry (Byram et al. 1966 in Albini 1976). The moisture of extinction is much lower for light, airy fuels such as fine grass, about 12 to 15 percent (Sneeuwjagt 1974 in Albini 1976), than it is for dense fuel beds such as pine needles, in which it has been measured at 25 to 30 percent (Rothermel and Anderson 1966 in Albini 1976). Under favorable burning conditions, the moisture of extinction has little effect on fire behavior, but when "conditions for burning are poor, it can cause significant changes in predicted fire behavior" (Rothermel 1983).

(3) Slope. The steepness of slope is measured as the rise of the ground in feet for every horizontal foot traversed, commonly referred to as "rise over run."

Percent Slope = Rise / Run x 100

Percent slope can be measured directly with instruments or calculated from topographic maps.

(4) Wind. Both windspeed and direction are used as inputs to the Fire Behavior Prediction System.

(a) Midflame windspeed. The speed of the wind is measured at the midpoint of the height of the flames because this best represents the wind that blows directly on the fire. Most weather forecasts, and most weather measurement stations, give the windspeed at 20 feet (6 meters) above the ground or above local obstructions. For fire behavior calculations, the 20-foot windspeed is reduced to the speed occurring at the midflame height. This compensates for the friction effect of vegetation and land surface that slows the speed of the wind. The adjustment factor varies with vegetation type, amount of canopy closure, and position on slope.

20 Foot Windspeed x Wind Adjustment Factor = Midflame Windspeed

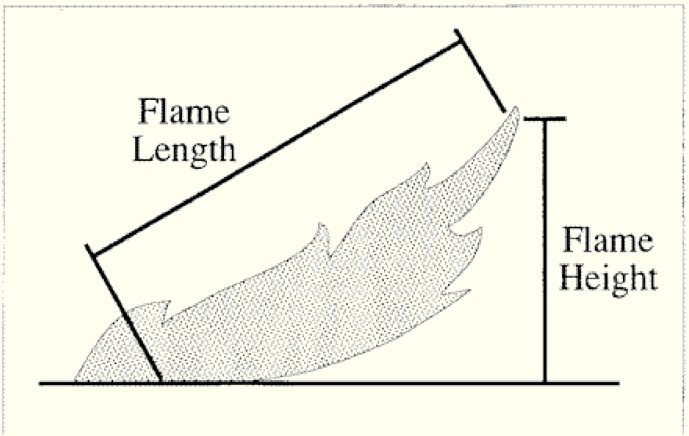
(b) Effective windspeed. As an intermediate step in obtaining solutions to the fire spread model, effective windspeed is determined. This value integrates the additive effects of slope steepness with a wind that is moving across or up a slope.

c. Outputs of the Fire Spread Model. The accuracy of predictions depends on how representative the fuel model chosen is of the fuels on the site, how accurately inputs are measured or estimated, and to what degree the situation meets the spread model assumptions. For predictions to be within a factor of two of actual fire behavior (from one-half to two times) is considered to be an acceptably accurate estimate (Norum 1993). The model is flexible enough that an experienced practitioner can make fairly good projections of fire behavior by carefully estimating or measuring the input values and tempering the results with judgment. Personal experience in a particular fuel type is necessary for refining output from this model.

(1) Forward rate of spread. One of the most important measures of fire behavior is the speed at which the fire moves across the landscape. The spread model calculates the rate of spread at the head of fire when the fire reaches its full, steady state speed. It predicts the speed of a fire burning in surface fuels, spreading on a single, unified front, that is not influenced by other ignitions. Rate of spread is generally stated in chains per hour, feet per minute, or meters per minute.

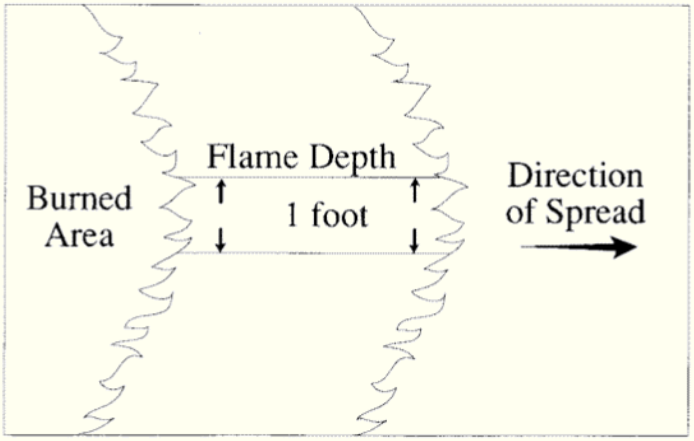
(2) Flame length. A second spread model output is the length of the flames when the fire has reached its full, forward rate of spread. Flame length is the distance along the slant of the flame from the midpoint of its base to its tip Flame height is the perpendicular distance from the ground to the flame tip and is not predicted by the fire spread model.

The average length of flame, measured along the slant of the flame from the midpoint of its base to its tip.



(3) Fireline intensity. Fireline intensity describes the nature of a fire in terms of its rate of energy release. Fireline intensity is the amount of heat given off by a fire along each foot of the leading edge of the fire each second, usually expressed as Btu per lineal foot of fireline per second.

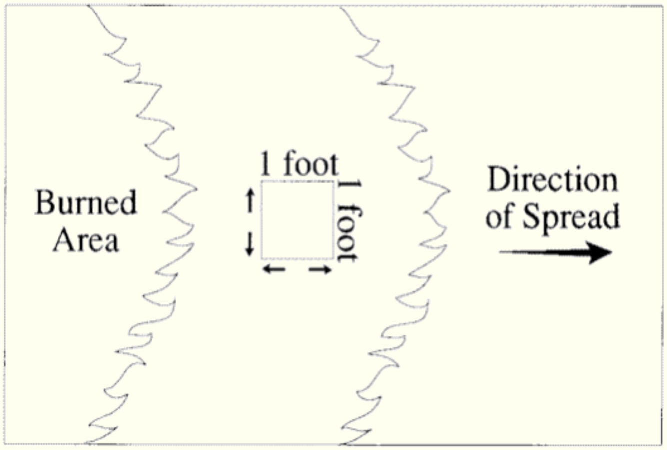
Rate of heat release in each **lineal foot** of the flaming front of a fire.



Btu's/lineal foot of fireline/second

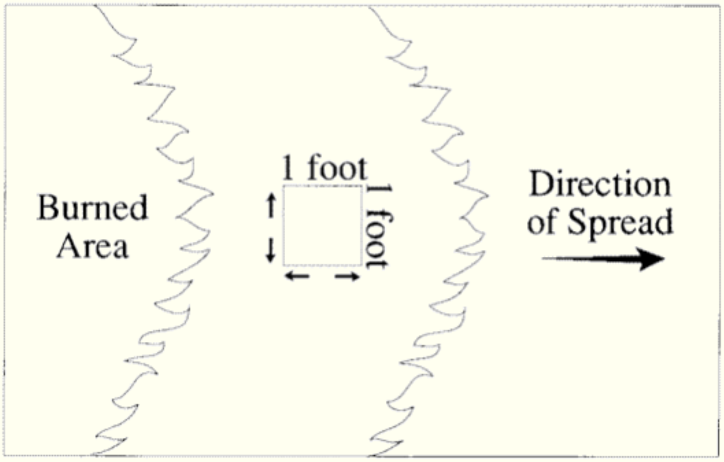
(4) Heat per unit area. Another measure of the energy released from a fire is heat per unit area. It is the total amount of heat released in each square foot of the flaming fire front, usually expressed as Btu per square foot. All of the heat given off in the flaming front is included in this value, regardless of the length of time that the flaming front persists. For a given area with a specific amount and distribution of fuel, heat per unit area is inversely related to fuel moisture content. Heat released in flaming combustion that occurs as fuels burn out after the flaming front has passed is not included in the heat per unit area value.

Rate of heat release in each **square foot** of the flaming front of a fire.



Btu's/square foot/minute

(5) Reaction intensity. Reaction intensity is a rate of heat release per unit area of flaming fuels, usually expressed in Btu per square foot per minute. This is the amount of energy released each minute by a square foot of flaming front, compared to heat per unit area which measures the total amount of energy given off per square foot. For a given fuel complex, reaction intensity can vary significantly with differences in moisture content.



Rate of heat release in each **square foot** of the flaming front of a fire.

Btu's/square foot/minute

d. Other predictable aspects of fire behavior.

(1) Probability of ignition. The probability of ignition, expressed as a percentage, is an estimate of the probability that a spark or firebrand landing on representative fuels will start a fire (Rothermel 1983). It is based on the amount of heat required to bring fine fuel to ignition temperature. Model inputs are fine fuel moisture, ambient air temperature, and the amount of shade.

(2) Maximum spotting distance. For many fuels situations, it is possible to make reasonably accurate estimates of the maximum distance to which fire may spot ahead by airborne embers (Rothermel 1983). The inputs required include the source of the embers, i.e. whether it is burning piles or trees; the species of tree, and their size and shape; the topography at and downwind from the fire; and the 20 foot windspeed. The model calculates the farthest distance a live ember is likely to be carried. It does not estimate how many burning embers will be lofted, or if the ember will ignite a spot fire. However, a combination of maximum spotting distance with the probability of ignition provides a workable idea of how far a fire may spot and the probability that it will cause a new fire.

(3) Crown fires.

(a) Classes. Van Wagner (1977) grouped crown fires into three classes based upon their dependence on the behavior of the surface fire.

i. Passive crown fires are those in which trees torch as individuals, ignited by the surface fire. These fires spread at essentially the same rate as surface fires. Trees torch within a few seconds with the entire crown enveloped in flames from its base to the top.

ii. Active crown fires are those in which a solid flame develops in the crowns. The surface and crown fires advance as a single unit dependent upon each other.

iii. Independent crown fires advance in the crowns alone, independently of the behavior of the surface fire.

(b) Crowning potential. The conditions necessary to cause the ignition of the crowns of trees or tall shrubs can be estimated. A probability of crown fires can be calculated, given the foliar moisture content and the height of the lowest part of the crowns. From these, an estimate can be derived of the fireline intensity needed to ignite the crowns (Rothermel 1983).

(c) Wind-driven vs. plume-dominated crown fires. The following discussion is taken from Rothermel (1991).

i. Wind-driven crown fire. A running crown fire can develop when winds blow flames from torching trees into adjacent tree crowns, or slope effectively accomplishes the same thing. Strong winds are the major force pushing the fire, and its spread rate can be greatly accelerated by slope. A strong convection column rapidly develops that is tipped over by the wind.

ii. Plume-dominated crown fire. A plume-dominated crown fire behaves quite differently from one driven by wind. Plume-dominated crown fires occur when windspeeds are fairly low. A strong convection column develops that rises above the fire, rather than leaning over before the wind. Air movement within the convection column generates the winds that cause significant rates of crown fire spread.

(d) Predicting size and intensity of crown fires. Rothermel (1991) presents methods for estimating and displaying the important elements of the behavior of a wind-driven crown fire. The model is applicable to coniferous forests of the northern Rocky Mountains, or forests with similar structure and fuels. Using these methods, an experienced fire behavior analyst can predict the rate of spread of a wind-driven crown fire, the length of flames, the time period when a particular crown fire will run, the probable area and perimeter of the crown fire, and the maximum rate of crown fire spread.

A method for calculating and comparing the power of a fire with the power of the wind is provided. The power of the fire is the heat energy released by combustion that drives the convection column, expressed as foot pounds per second per square foot. If the power generated by the fire is close to or exceeds that of the wind, a plume-dominated crown fire may develop. The onset of a plume-dominated fire may cause a sudden acceleration of the fire and faster spread rates than predicted. The model can thus predict the potential for onset of a plume-dominated fire, but not its behavior.

5. Relationships between Fire Behavior and Fire Effects. Few fire effects are known to be directly related to the behavior of the surface fire, that is to its spread rate, flame length, or rate of heat release. The following effects can be estimated from outputs of the Fire Behavior Prediction System.

a. Crown scorch height. There is a direct relationship between crown scorch height and flame length, ambient air temperature, and wind. All of these variables are used to measure the height above the surface of the ground that lethal temperatures occur. The height of tree crown scorch can be predicted from these values, using a model (SCORCH) in the Fire Behavior Prediction System. (See XII.D.1.a, this Guide.)

b. Tree mortality. A model (MORTALITY) estimates the percentage of tree mortality from scorch height, tree height, tree diameter, and crown ratio for eight species of conifers that occur in the northern Rocky Mountains. (See XII.D.1.b, this Guide.)

c. Total heat pulse to the site. Heat per unit area is a good estimate of the total heat pulse to the site when all of the fuel that is burned is consumed by the passing flame front. However, because this value does not account for long-term burnout of heavy fuels or organic soil layers, heat per unit area is not a very good estimate of the heat regime of the fire when much of the fuel, litter, or duff consumption occurs after the flaming front has passed.

6. Aspects of a Fire's Heat Regime that Cannot Presently Be Predicted. Many aspects of the heat regime of a fire cannot presently be predicted with any known model. Many of the most important and influential effects of fire on a site and its biological components are related to aspects of the heat regime of a fire that are not described by the Fire Behavior Prediction System.

Fireline intensity, as described in II.B.3.b.(3), is a rate of heat release that is related to flame length. However, the release of energy in flames has little relationship to the amount of subsurface heating (Hungerford 1989). Peak subsurface temperatures and the amount and duration of soil heating are not related to any value predicted by the Fire Behavior Prediction System. The effects of fire on fuels, soils, watershed, understory vegetation, and wildlife habitat cannot be estimated from measures of fireline intensity or flame length alone.

a. Fuel burnout time. This is the length of time that fuels continue to burn after the flaming front has passed, including all phases of combustion. The length of the fuel burnout period is related to fuel properties and fuel moisture but cannot be estimated by any known method.

b. Duration of smoldering and glowing combustion. Smoldering and glowing combustion are related to the amount of fuel, its size class distribution, thickness of duff and organic layers, and the moisture content of heavier fuels and duff. We cannot presently predict the duration of time during which these combustion phases will occur.

c. Total heat pulse to the site. Total heat pulse considers not only the heat released in flames but also that released by smoldering and glowing combustion. Heat per unit area only includes the amount of heat that is released in the flaming front. Extensive studies in physics modelling is currently underway at the Intermountain Fire Sciences Lab which may provide means to calculate the total heat pulse to the site.

d. Soil heating. Most heat produced by the flaming front moves upward. Downward movement of heat from flames cannot presently be predicted, but it is not believed to be a significant source of subsurface heat. Most soil heating results from long term fuel, duff, and organic layer burnout. Neither this heat, nor its penetration into soil layers, has been modelled.

e. Burn severity. Burn severity is a term that qualitatively describes classes of surface fuel and duff consumption. Large diameter down, dead woody fuels and organic soil horizons are consumed during long-term, smoldering and glowing combustion. The amount of duff or organic layer reduction is also called depth of burn, or ground char (Ryan and Noste 1985). Because the amount and duration of subsurface heating can be inferred from burn severity, this variable can be related to fire effects on plants and soils. Factors regulating fuel and duff consumption, and thus burn severity, are discussed in Chapter III.B.2. and 3. The relationship between burn severity and its effects on plants is described in Chapter VI.B.1.c. and VI.B.2.c.

(1) Descriptive classes. An example of a set of burn severity classes is given below. Agency specific guidelines for assessing burn severity are described in USDI-NPS (1992).

(a) Unburned.

(b) Scorched. Foliage is yellow; litter and surface vegetation are barely burned or singed.

(c) Low severity. Small diameter woody debris is consumed; some small twigs may remain. Leaf litter may be charred or consumed, and the surface of the duff may be charred. Original forms of surface materials, such as needle litter or lichens may be visible; essentially no soil heating occurs.

(d) Moderate severity. Foliage, twigs, and the litter layer are consumed. The duff layer, rotten wood, and larger diameter woody debris is partially consumed; logs may be deeply charred; shallow ash layer and burned roots and rhizomes are present. Some heating of mineral soil may occur if the soil organic layer was thin.

(e) High severity. Deep ash layer is present; all or most organic matter is removed; essentially all plant parts in the duff layer are consumed. Soil heating may be significant where large diameter fuels or duff layers were consumed. The top layer of mineral soil may be changed in color; the layer below may be blackened from charring of organic matter in the soil.

(2) Relationship between fireline intensity and burn severity. There can be many combinations of fireline intensity and burn severity on any site, depending on fuel loading and distribution, and site weather and moisture conditions at the time of the fire. For example, given a site with good, continuous surface fuels, and a deep litter/organic layer, any of the following combinations of fireline intensity and burn severity can occur (as well as a lot of intermediate combinations).

(a) High fireline intensity/high burn severity. Both the carrier fuels and organic layer are dry. The result is a fire with high fireline intensity that exhibits vigorous fire behavior, that is also a deep burning, high severity fire. Flames are long, large fuels are removed, soil organic layers are consumed, and the long duration fire causes a significant amount of subsurface heating.

(b) High fireline intensity/low burn severity. The carrier fuels are dry, but the litter/duff layer is wet. The result is a fire with high fireline intensity, that exhibits vigorous fire behavior, but which is a very low severity fire because the organic layer is too wet to burn. Flames are long but little subsurface heating occurs.

(c) Low fireline intensity/high burn severity. The carrier fuels and surface litter are moist, and litter/duff layers are dry. The result is a fire of low fireline intensity that may barely cover the area, but of high burn severity wherever the litter/duff layer ignites because it is dry enough to burn. Even though the surface fire was of little apparent consequence, a significant amount of soil heating can occur, caused by the consumption of dry duff layers, peat, and/or large diameter downed woody fuels.

(d) Low fireline intensity/low burn severity. The carrier fuels are moist and the litter/duff layer is wet. The result is a fire with low fireline intensity that also has low severity.

(3) Application to shrub dominated communities. Burn severity concepts can also apply to litter and duff layers beneath isolated trees and shrubs.

(1) Low severity fire may just scorch the litter beneath the shrub or tree crown.

(2) A moderate severity fire may consume some basal litter and organic matter, but residual material remains. Some heating of deeper organic layers and soil may occur.

(3) A high severity fire removes all litter and duff, leaving only an ash layer. Significant amounts of soil heating can only occur where there is a high degree of consumption of thick, basal organic layers. Isolated patches of severely burned ground may occur where shrubs used to be, surrounded by extensive areas where little soil heating occurred.

f. Burn pattern. The pattern of a fire is the mosaic of burned and unburned vegetation and fuels. It can be further defined in terms of the degree of heating and consumption of fuels and vegetation, such as scorched compared to severely burned areas. A pattern can occur in the tree canopy, shrub canopy, in surface fuels, or in litter, duff, and organic layers. The size of the mosaic can vary from acres of scorched, consumed, and unburned patches in the canopy, to mosaic patterns of burned and unburned fuels and litter layers of only a few feet, or even inches. The effects of fire are closely related to the pattern of the fire, both on a large and small scale. Fire effects vary considerably with burn pattern because it reflects the variation in the fire's heat regime, above, at, and below the surface.

Significant variations in burn pattern are the result of differences in fuel continuity, fuel loading, fuel moisture, aspect, wind, and ignition methods and techniques. Whether a fire will become a surface or crown fire, and its effects on fuel consumption and soil heating, can be estimated by a person skilled in fire behavior or prescribed fire. However, there are presently no computational tools with which to predict the exact burn pattern that will occur.

C. Resource Management Considerations

1. Levels of Fireline Intensity. Different levels of fireline intensity, along with corresponding flame lengths, have special meaning both for the design of prescriptions for prescribed fire, and in wildfire management activities. From widely held and commonly agreed upon experience, the following are reliable rules (Rothermel 1983).

a. When fireline intensity is below 100 Btu per foot of fireline per second, flame lengths are less than 4 feet (1.2 meters).

(1) Fires can generally be attacked at the head or flanks of the fire by persons using hand tools.

(2) Handlines should be adequate to hold the fire.

b. Fireline intensity 100 to 500 Btu per foot of fireline per second; flame lengths are between 4 and 8 feet (1.2 to 2.4 meters).

(1) Fires are too intense for direct attack at the head of the fire by persons using hand tools.

(2) Handline cannot be relied upon to hold the fire.

(3) Equipment such as bulldozers, pumpers, and retardant aircraft may still be effective.

(4) Fires are potentially dangerous to personnel and equipment.

c. Fireline intensity 500 to 1,000 Btu per foot of fireline per second; flame lengths are between 8 and 11 feet (2.4 to 3.4 meters).

(1) Fires may present serious control problems, such as torching out, crowning, and spotting ahead.

(2) Control efforts at the head of the fire probably will be ineffective. Indirect attack is probably the only means of suppression.

(3) Fires are definitely dangerous to personnel and equipment.

d. Fireline intensity above 1,000 Btu per foot of fireline per second; flame lengths are greater than 11 feet (3.4 meters).

(1) Crowning, spotting, and major fire runs are probable.

(2) Control efforts at the head of the fire are ineffective by any known means of suppression. Indirect attack and tactical counterfiring may be the only means to slow the spread of the fire in certain directions.

(3) Fires are extremely dangerous to personnel and equipment in the immediate vicinity of the fire.

These values have obvious implications for holding actions on prescribed fires and suppression actions on wildfires. If only hand crews are available to hold a prescribed fire, and handlines are the only lines of control, then prescription variables (inputs to the spread model) should be set so that surface fires do not exceed 100 Btu per second per foot, nor flame lengths exceed 4 feet (1.2 meters).

2. Relationship between Moisture Content of Big Sagebrush and Fire Behavior. In vegetation types dominated by shrubs, moisture content of foliage can be a dominant factor in the behavior of wildland fires. Within a given geographical area, it is possible to determine threshold levels of foliar moisture content that relate to degrees of fire behavior activity and difficulty of control. In order to obtain such a database, foliar moisture content levels must be documented in areas where fires are occurring and fire behavior observations must be recorded. Sampling at established intervals over a period of several years and relating moisture levels to easily identifiable growth stages of the plants would provide the most useful information.

Threshold levels of moisture that relate to fire behavior in sagebrush have been determined for Nevada and eastern Oregon.

a. Nevada. When Greg Zschaechner worked for the Bureau of Land Management in Nevada on the Great Basin Live Fuel Moisture Project, he established guidelines that relate the moisture content of big sagebrush *(Artemisia tridentata)* to fire behavior and effective suppression tactics. Suppression tactics are included in the following descriptions because they provide additional description of the behavior of the fire. These levels are most accurate within Nevada but may serve as general guidelines elsewhere.

(1) 181 percent and above. Fires will exhibit VERY LOW FIRE BEHAVIOR with difficulty in continued burning. Residual fine fuels from the previous year may carry the fire. Foliage will remain on the stems following a burn. Fires can generally be attacked at head or flanks by persons using handtools. Handlines should hold the fire without any problems. Fires will normally go out when the wind dies down.

(2) 151 percent to 180 percent. Fires will exhibit LOW FIRE BEHAVIOR with fire beginning to be carried in the live fuels. Both foliage and stem material up to 1/4 inch (0.6 centimeters) in diameter will be consumed by the fire. Burns will be generally patchy with many unburned islands. Engines may be necessary to catch fires at the head. Handline will be more difficult to construct but should hold at the head and flanks of the fire.

(3) 126 percent to 150 percent. Fires will exhibit MODERATE FIRE BEHAVIOR with a fast continuous rate of spread that will consume stem material up to 2 inches (5.1 centimeters) in diameter. These fires may be attacked at the head with engines but may require support of dozers and retardant aircraft. Handline will become ineffective at the fire head but should still hold the flanks. Under high winds and low humidities, indirect line should be given consideration.

(4) 101 percent to 125 percent. Fires will exhibit HIGH FIRE BEHAVIOR leaving no material unburned. Head attack with engines and dozers will be nearly impossible on large fires, but may still be possible on smaller, developing fires. Flanking attack by engines and indirect attack ahead of the fire must be used. Spotting should be anticipated. Fires will begin to burn through the night, calming down several hours before sunrise.

(5) 75 percent to 100 percent. Fires will exhibit EXTREME FIRE BEHAVIOR. Extreme spread rates and moderate to long range spotting will occur. Engines and dozers may be best used to back up firing operations and to protect structures. Indirect attack must be used to control these fires. Fires will burn actively through the night.

(6) 74 percent and below. Fires will have ADVANCED FIRE BEHAVIOR with high potential to control their environment. Large acreage will be consumed in very short time periods. Backfiring from indirect line such as roads must be considered. Aircraft will need to be cautious of hazardous turbulence around the fire.

b. Eastern Oregon. Fire behavior and its relationship to moisture content in sagebrush has been monitored on Oregon rangelands east of the Cascades (Clark 1989). The following moisture levels indicate how readily a fire can propagate, given that adequate fine fuels are present between sagebrush plants to carry the fire, or that sagebrush density is high enough for flames to reach between plants where herbaceous fuels are sparse.

(1) Above 90 percent. Fire behavior is docile. The fire may or may not spread and is easy to control.

(2) 60 to 90 percent. Fire is much more difficult to control. Fire is likely to burn actively throughout the night, especially if wind is present.

(3) Less than 60 percent. The fire displays extreme fire behavior and rates of spread, and is essentially uncontrollable by normal suppression methods.

3. Effect of Fuel Type Changes on Fire Behavior. The dominating factor regulating fire behavior is wind in some fuel types and moisture content in others. The behavior of fires in fuel types with a large component of fine materials, such as the grass models, is most influenced by wind. Fuel moisture is much more important than wind in regulating the activity of fires in fuel types with a lot of larger diameter, dead woody fuels. Wind, while influential, is not so dramatically important in heavy fuels as it is in grass or shrub type fuels.

Fire behavior can drastically change when a fire moves into a different fuel type. If a fire moves from an area of logging residue to one dominated by cured grassy fuels, flame length and fireline intensity will probably decrease, but the rate of spread is likely to increase significantly. An optimal prescription for burning the logged unit to reduce hazard fuels would include low moisture content in smaller size classes of fuels and low windspeeds. Under these conditions, the desired amount of consumption in the harvested area would be achieved, and any escape into the grass fuels outside of the unit could easily be caught.

4. Effect of Long-Term Drying on Heat Release. Long periods of limited precipitation result in deep drying of the surface organic layers. Deeper drying of the entire fuel complex leads to an increase in fire behavior because of greater involvement of larger fuels and surface organic fuels in the fire front. Because more fuels burn in the initial stages of flaming combustion, fireline intensities and flame lengths can be greater. More heat can also be generated during smoldering and glowing phases of combustion, as deeper organic layers may burn. Fire effects may be much more notable than if the site had burned under less droughty conditions.

5. Burn Pattern. When igniting a prescribed fire, the pattern of burn that is being obtained should be noted throughout the ignition period. If the desired mosaic is not being obtained, alteration of ignition pattern may change the percent of the prescribed fire area that is actually being covered by fire.

6. Firewhirls. Firewhirls are tight, spinning vortices filled with flame and hot gas that have the appearance of a small tornado of fire. They can cause severe difficulty in controlling a wildfire or prescribed fire by spreading pieces of flaming material great distances beyond the project area.

When igniting a prescribed fire using strip headfires, it is important to let one strip of fire burn down in intensity before igniting the next strip. This avoids concentrated mutual convection, competition for incoming air, and a high probability of initiating firewhirls at the ends of the strips. Also, by skillfully designing the ignition pattern and sequence, the risk of firewhirls developing on lee slopes, and where two fires merge, can be minimized.

D. Methods to Monitor Fire Behavior and Characteristics

Fire prescriptions contain elements that define ranges of acceptable weather and moisture conditions that produce the desired fire behavior and characteristics. Monitoring for a prescribed fire can include monitoring of weather and fuel moisture before the fire to determine the daily weather patterns in a particular area and to determine how close moisture conditions are to the prescribed range. Some factors vary diurnally, such as temperature, relative humidity, and the associated moisture content of small diameter fuels. Other prescription elements, such as moisture content of soil organic layers or live fuel moisture content, decrease slowly, and weekly monitoring is often adequate to detect change.

It is important to monitor all elements of the prescription during a fire to determine that the fire remains within prescription, that the fire behavior predictions were adequate, and to correlate with the subsequent effects of the fire treatment. Whenever possible, information on fuel moisture, fire behavior, and fire characteristics should be obtained in the same location(s) as fire effects data collection occurs. In order to most effectively monitor rates of fire spread, flame length, and burn severity, some equipment may need to be installed before a fire.

If site characteristics vary on the burned area, specific site attributes should be documented as observations about fire behavior are made. Fuel type, vegetation type, slope, and aspect should be recorded, as well as a notation about the location where the observation is made. Whether the fire is a heading, backing, or flanking fire should be noted at the same time as observations are made.

1. Burning Conditions.

a. Fuel moisture. Fuel moisture is a critical determinant of fire behavior and characteristics. Techniques to monitor fuel moisture are described in Chapter III.D.4, this Guide.

b. Weather. An important part of monitoring fire behavior and characteristics is to have a good record of weather that occurred during the time that a fire occurs. A standard set of weather observations should be taken at regular intervals during the fire: temperature, relative humidity, windspeed and direction, clouds or other indicators of instability, and the presence of thunderstorms. Standard procedures for monitoring weather are detailed in Finklin and Fischer (1990). Agency specific guidance on weather data collection is available in USDI-NPS (1992).

2. Fire Behavior and Characteristics. Agency specific guidelines for monitoring fire behavior and characteristics are described for forests and for grassland and brush types in USDI-NPS (1992). The following description provides additional methods.

a. Rate of spread. Observations of rate of fire spread should only be taken after the fire has reached a steady state, because this is what the fire behavior system predicts. Rate of spread measurements are difficult to document on prescribed fires with center or perimeter firing patterns, or narrow strip headfires. In these situations the fire often has not reached a steady state, or its behavior is influenced by the ignitions that have occurred in adjacent areas. Whether the fire is heading, backing, or flanking at the point of observation should be noted. The following discussion is taken largely from Zimmerman (1988).

(1) Visual observation. Visual observation and pacing of distances can be used to take rate of spread measurements, particularly on a slowly moving fire. A stopwatch is used to determine how long it takes a fire to cover a specific distance. Rate of spread is calculated from the time/distance relationship.

(2) Metal tags. Numbered metal tags can be thrown at or near the flaming front. A stopwatch is started when the front crosses a tag and a second tag is thrown ahead of the fire. When the flaming front crosses the second tag, the stopwatch records the elapsed time. The distance between the two tags is measured by pacing or steel tape, and the spread rate calculated.

(3) Grid marking system. When high spread rates are expected, and/or when it is not safe to be immediately adjacent to the fire, fire behavior can be measured using a grid system installed before the fire. Spacing of markers should be related to the expected rate of forward spread of the fire. Reference point markers can consist of materials such as flagging tape tied to branches or poles painted with bright paint. Times are recorded with a stopwatch or wrist watch as the fire burns past each marker, and rate of spread is determined.

(4) Sketch map. Sketch maps of the fire perimeter can be made at different times during the period of fire growth, a useful technique if reference points are plentiful or the fire will cover a large area. This method requires a good vantage point or the use of an aircraft. Rate of spread can later be calculated by dividing the distances between different landmarks by the time periods it took to cover these distances.

(5) Photography. Pictures of the fire can be taken at specific intervals and time noted when each photo is taken. A 35 mm camera with split lens can be used (Britton et al. 1977), in which one side of the image is focused on a watch, and the other on the flame. Cameras are now commercially available that record date and time on each image. The use of black and white infrared film greatly increases the value of this technique because it increases the quality of an image recorded through visually obscuring smoke.

(6) Video camera. Video cameras can be very successfully used when monitoring fire behavior. Time and other observations can be recorded on an audio track while recording the visual image. The advantages of video cameras include the potential for making a complete record of fire as it burns in specific areas, the fact that image quality can be immediately assessed, and that cameras are relatively inexpensive and very portable.

A computerized image analysis system has been used to study video tapes. A grid representing a known size or distance is set on the first frame, and subsequent measurements can be made from the screen image (McMahon et al. 1987).

b. Flaming residence time. Residence time is the amount of time that it takes the flaming front of the fire to pass a particular point. Residence time can be difficult to measure because of the indefinite trailing edge of the fire as concentrations of fuel continue to flame. It can be estimated from observations, still photography, or a video camera. The video position analyzer system (ibid.) also can be used to obtain more accurate residence time estimates. Use of infrared sensors or film are extremely useful when smoke obscures flames.

c. Fuel burnout time. Residence time discussed above is only a measure for flaming combustion. For monitoring that will later be related to fire effects, an estimate of the total duration of smoldering combustion of large diameter fuels and duff layers is important. Observation, repeated photography of the same points particularly with black and white infrared film, repeated video camera images, or a Probe-eye® can record fuel burnout time. Infrared images can sense higher temperatures caused by continued smoldering or glowing combustion when no visible signs of combustion are present. While it is not important to document the duration of long-term combustion to the exact minute, it is important to note whether smoldering combustion lasts for only a few minutes, or a few hours, or several days.

d. Flame length. Flame length is measured along the slant of the flame. The accuracy of estimation of flame length can be increased by installing reference points that provide scale. Steel posts with 1-foot sections alternately painted red and white or metal flags attached every 3 feet (the choice depends on the expected scale of the flames) set in the burn area work very well (Rothermel and Deeming 1980). These markers can be the same as those used to measure rate of fire spread.

(1) Observations. Flame length data are usually obtained from visual observations of average flame length at set intervals. Flame length is usually recorded at the same time as rate of spread observations are made.

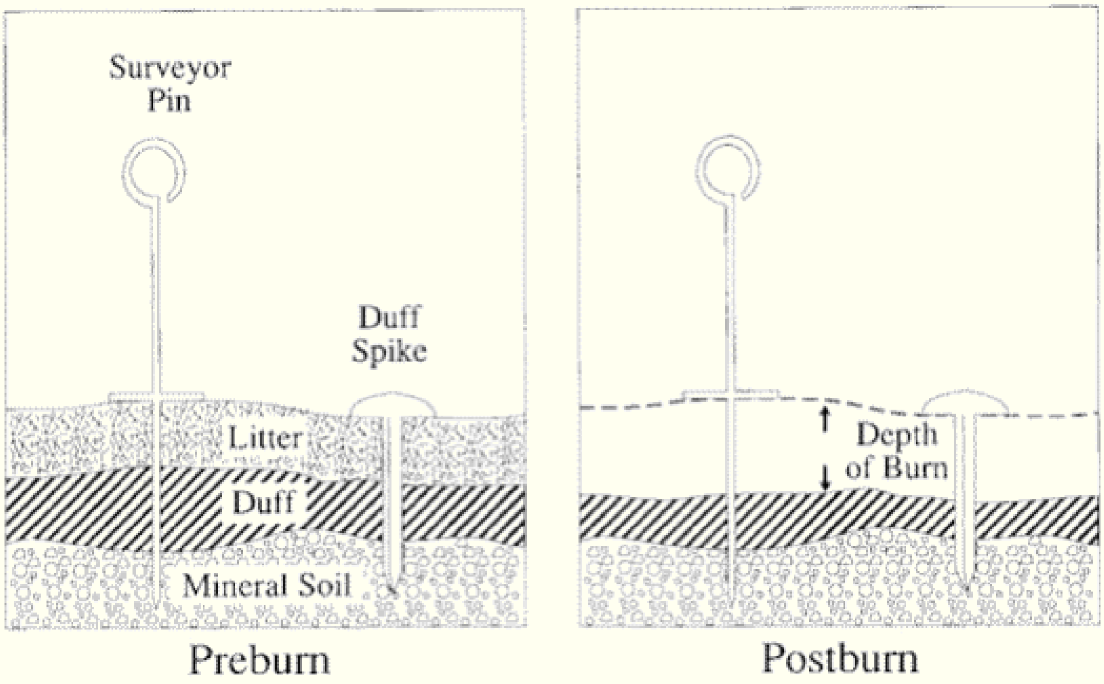
(2) Photography. Flame length can be documented with cameras and time and location of observation of each exposure recorded. Accuracy is enhanced by use of infrared film.

(3) Video camera. Not only are video cameras an excellent way of documenting fire behavior, the passive image analyzer mentioned above (McMahon et al. 1987) allows a very accurate measurement of flame length. After a grid of known size is established on the first frame, the tape is advanced until a representative flame is seen on the screen. The image is frozen on the screen, and the flame is outlined on the screen with a cursor. Computer software then calculates flame length.

e. Burn pattern. A map of the burned area can be made at both a gross and detailed scale. For general monitoring purposes, a map of the burned area can show areas where the tree or shrub canopy was removed, areas where the fire was an underburn, and areas the fire did not burn at all. Information on burn pattern can be obtained by a walk through the burned area, by long transects, or with photography. A low elevation aerial photo, or an oblique photo taken from a high vantage point such as a hill or a tree, can be measured with a dot grid to determine burn pattern. For large wildfires, satellite imagery can be used to obtain information on the pattern of burned and unburned areas, and where the fire was a surface fire or a crown fire. When choosing imagery for analysis, it must be remembered that up to about 2 weeks may pass before scorch damage to overstory tree foliage is apparent.

f. Burn severity/Depth of burn. The pattern of burn severity on the surface of the ground can be quite complex, because it varies with the distribution of prefire fuel loading and arrangement, thickness of litter and duff layers, and moisture content of surface and ground fuels. While mapping the pattern of burn in the surface fuels and vegetation for an entire burned area may be too large a task, burn severity, and the degree of canopy removal, should be noted in the areas where fire effects monitoring sites are located.

Surveyor pins or bridge spikes can be used in easy and practical way to monitor depth of burn. The pins or spikes are pounded into the ground before the fire, with a cross piece or top of the spike level with the top of the litter layer. After the fire, the amount of pin exposed is a measure of the depth of organic material removed. The amount of residual organic layer at each pin site can be measured to obtain an estimate of duff removal. Use of an inexpensive metal detector can make it much easier to relocate metal pins after the fire.



3. Potential Control Problems. The occurrence of any of the following during a prescribed fire should be noted and recorded and the Burn Boss or Fire Behavior Analyst notified.

a. Spotting. If spotting is occurring outside the burn perimeter, record the time of occurrence, distance from the fire front, and location on a map.

b. Torching or crowning. Torching or crowning trees may produce spots and may indicate that the situation requires extra caution. Note the time and location of occurrence and any relationship observed with surface fire behavior.

c. Firewhirls. The location and time of any firewhirls should be recorded. Observations about the fuels in the area of the fire whirls, or any relation to ignition method or technique, should be noted.

d. Fire behavior exceeding prescription limits. Any observation of rate of spread or flame length that exceeds specified limits could provide a potential control problem. Fire behavior less than that predicted is not necessarily a control problem, but can lead to an improper site treatment, and should be reported.

E. Summary

Knowledge of the behavior and characteristics of wildland fire are important both for managing fire and for understanding and interpreting the effects of fire. The heat regime created by a fire varies with the amount, arrangement, and moisture content of flammable materials on a site. Trained and experienced people can predict (within a factor of two) some aspects of the behavior and heat release of a flaming front of a fire, and some associated fire effects such as crown scorch. However, many fire effects are related to characteristics of fire that are not related to the behavior of the flaming front and cannot presently be forecast.

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CHAPTER III - FUELS

By Melanie Miller

A. Introduction

Fuel characteristics strongly influence how a given site will burn under specific environmental conditions. Fire also has an effect on fuels, because fire requires the consumption of fuel. Besides removing fuel, fire can result in the creation of additional surface fuel, as vegetation drops fire-killed leaves, needles, and twigs, and dead shrubs and trees fall and become part of the surface fuel layer.

All effects of fire on resources result from its effect on fuels, because the way that fuels burn determines the heat regime of a fire. Each fire varies in the amount of fuels that burn, the size class distribution of fuels that burn, the rate at which fuels burn, how much soil organic matter burns, and whether living plants become fuel. The nature of fuel consumption determines the peak temperatures reached, the duration of heat, and the stratification of heat above and below the surface.

Fuels such as litter, snags, and downed trees, have important effects on a site. Freshly deposited litter protects the soil surface from erosion by raindrops. Unburned logs and fallen fire-killed trees provide locations for mycorrhizae, nitrogen fixation, and habitat for birds, mammals, and insects. Standing snags provide habitat for many animal species that utilize this specific habitat.

This chapter will discuss the factors that regulate the effect of fire on fuels. Different types of fuels are defined, and the factors that control the amount of fuel and organic layer consumption are described. Dead and live fuel moisture content are discussed in great detail because moisture content is the most important determinant of the combustion process and the heat regime of the fire. Basic principles of fuel succession, the changes in the fuel complex over time, are summarized. Those properties of fuels that affect the behavior of a flaming fire are described in Chapter II of this Guide, Fire Behavior and Characteristics. Those aspects of combustion that affect smoke production are discussed in Chapter IV, Air Quality, this Guide. The role of downed logs and organic matter in regulating soil nutrients and their relationship to fire are discussed in the Soils chapter of this Guide, Chapter V. Wildlife use of dead woody material as habitat is described in Chapter VII, Wildlife Habitat.

B. Principles and Processes

1. Fuel Classification. Fuel is all vegetative biomass, living or dead, that can be ignited by lightning or an approaching fire front. Wildland fuels have been grouped into various classes.

a. Natural fuels vs. activity fuels. Natural fuels result from plant growth and death, loss of foliage, branch breakage, and tree blowdown. Activity fuels are similar to natural fuels but they are distributed differently in time and space due to human activity such as logging, thinning, chaining, and herbicide use.

b. Down, dead woody fuels. This class of fuels includes dead twigs, branches, stems, and boles of trees and shrubs that have fallen and lie on or above the ground (Brown et al. 1982). Wood can be either sound or rotten. Sound wood is essentially intact. It may have checks or cracks, but it still retains its structure. Rotten wood is partially decomposed. Material is punky or can be easily kicked apart. It can be important to distinguish between sound and rotten large diameter woody fuels because their moisture retention and combustion characteristics are very different. (See B.2.a.(3) and B.4.d.(3), this Chapter.)

c. Soil litter and organic layers.

(1) Litter. Litter is the top layer of the forest floor, typically composed of loose debris such as fine twigs, and recently fallen leaves or needles, little altered in structure by decomposition. Litter can also include loose accumulations of debris fallen from rangeland shrubs, and dead parts of grass plants lying on or near the surface of the ground. Some surface feather moss and lichen layers are also considered to be litter because their moisture response is similar to dead fine fuel.

(2) Organic layers.

(a) Duff. Duff is the partially decomposed organic material of the forest floor that lies beneath the freshly fallen twigs, needles and leaves. It is equivalent to the fermentation and humus layers of soil.

(b) Organic soils. Soils that are essentially composed of deep layers of organic matter form wherever production of organic matter exceeds rates of decomposition. They frequently develop in poorly drained areas where plant material partially decomposes in water or in saturated environments. Organic soils can be extensive in wetlands and in cool, moist climates (Buol et al. 1973). The amount of incorporated mineral material can vary significantly. The organic content of these soils can burn if soil moisture content is low enough.

d. Live fuels. Live fuels are living vascular plants that may burn in a wildland fire. Live fuels include trees, shrubs, grasses and grass-like plants, forbs, and ferns. Because of seasonal variation in their moisture content, the flammability of their foliage can vary significantly. Herbaceous plants, i.e., grasses and forbs, can cure, changing from a live fuel to a dead fuel. The leaves and older needles of trees and shrubs dry and fall from the plants, adding to the surface litter layer at the end of the growing season. Living plants may contain a large component of dead material, such as dead branchwood in older shrubs. This increases their flammability and the likelihood that the entire plant will be consumed by fire. Live fuel moisture cycles are described in greater detail in section B.5. of this chapter.

e. Fuel strata. Fuels have been classed as surface, ground, aerial, or ladder fuels. These terms are described in Chapter II.B.1.a., this Guide.

f. Total fuel vs. available fuel. Total fuel is the total amount of fuel present on a site. Available fuel is the amount that can burn, under a given set of conditions. The amount of available fuel depends on fuel size, arrangement, and moisture content (Brown and See 1981). Fuel size can affect availability if there are inadequate amounts of smaller sized fuels to burn and transfer enough heat to larger size fuels to raise them to ignition temperature. Standing tree boles are not considered to be available fuel because they are extremely unlikely to burn in wildland fires, except for smoldering in punky snags.

There can be long-term changes in fuel availability. The total amount of fuel within a stand increases as plants grow, while the distribution of fuel within a stand changes when snags or branches fall or foliage drops. There can also be short term changes in availability due to fuel moisture content. At any given point in time, the most important factor affecting fuel availability is its moisture content, because this determines whether fuel can ignite, and whether it can sustain combustion.

2. Factors Regulating Dead Fuel Consumption.

a. Relationship to physical and chemical properties of fuel. The key fuel properties that affect fire behavior were described in Chapter II.B.3.b. The following discussion explains how some of these factors influence fuel consumption.

(1) Fuel size. Fuels less than 1/4-inch diameter are almost completely consumed by fire over a wide range of burning conditions. Most branchwood between 1/4-inch and 3 inches is also consumed (Martin et al. 1979). A fair prediction of the consumption of large diameter dead woody fuels is possible if the average preburn diameter is known (Reinhardt et al. 1991).

(2) Fuel continuity. Fuel continuity relates to the proximity of individual pieces of fuel and also of different fuel strata. It affects fire spread, how much of an area ignites, and how much fuel is consumed. Breaks in fuel continuity contribute to patchy fire spread and may result in patchy fuel consumption.

(a) Forests. Large diameter fuels in local accumulations are more likely to be consumed than if these fuels are scattered. Anderson (1983) found that large downed woody fuels need to be within a distance of about 1.5 diameters of each other for interactive burning to occur.

(b) Rangelands/grasslands. Fuel consumption in range and grass types can be closely related to fuel continuity. If fuels are sparse, windspeed may not be adequate to spread the fire, limiting the amount of fuels that are ignited and consumed.

(3) Quality. Wood may be sound, rotten, or partially rotten. In north Idaho, consumption of rotten wood was greater than that of sound wood, even though moisture content of rotten wood was higher. Consumption of completely rotten pieces was higher than that of partially rotten pieces (Reinhardt et al. 1991).

(4) Heat content. The heat content of wood is about 8,000 Btu per pound (Albini 1976). Pitch adds to the flammability of wood because its heat content is about 15,000 Btu per pound (Carmen (1950 in Byram 1959). Pitchy fuels can burn at a much higher moisture content than those without pitch. A damp pitchy stump that is ignited is often completely consumed by fire.

(5) Fuel moisture content. The major effect of moisture on small fuel consumption is simply whether fuels are dry enough to ignite. Eighty to 90 percent of fine woody forest fuels are consumed wherever fire spreads (Brown et al. 1985). This is also true for fine rangeland fuels. The proportion of large diameter woody fuels consumed is more strongly influenced by their moisture content than by any other factor (Reinhardt et al. 1991).

b. Relationship to phase of combustion. The phase of combustion during which dead woody fuels are consumed is related to their size.

(1) Small diameter fuels. Fine fuels tend to be consumed during flaming combustion. However, the arrangement of small woody fuels sometimes does not provide enough mutual heating during the flaming state for complete consumption to occur. Blackened branches may burn off or fall into the ash and generate enough mutual heat for more flaming combustion to occur. Eventually the amount of heat that is generated decreases and can no longer support flaming, and the remaining consumption of these small pieces occurs by smoldering and glowing combustion (Norum 1992).

(2) Large diameter fuels. While the surface layer of woody fuels may initially support flames, most of the consumption of large woody fuels, both sound and rotten, occurs in the smoldering and glowing phases of combustion. Glowing combustion in large woody fuels commonly lasts for 10 to 20 times longer than the flaming phase (Anderson 1983).

3. Factors Regulating Consumption of Duff and Organic Soils.

a. Moisture content. As is true for large diameter woody fuels, moisture content is the most important variable influencing consumption of duff and soil organic layers. Duff and soil temperatures remain below the boiling point of water (100 C.) until all moisture is evaporated (Hartford and Frandsen 1992). Heating of organic layers to the high temperatures required for ignition cannot occur while moisture is present.

Specific relationships have been observed between duff moisture and duff consumption. At less than 30 percent duff moisture content, duff layers burn on their own once ignited, a threshold level observed in the southwest U. S., Pacific northwest, and the northern Rockies (Brown et al. 1985). At 30 to 120 percent duff moisture content, the amount of consumption of duff depends on the amount of consumption of associated fuel. When duff moisture content is greater than 120 percent, duff essentially will not be consumed.

Similar relationships have been found for organic soils. Peat is a deposit of slightly or non-decayed organic matter, while the organic content of muck is markedly decomposed (Buckman and Brady 1966). Peat burns well when its moisture content is below about 30 percent (Craighead 1974 in Hermann et al. 1991). Blocks of organic soil from south central Florida sustained smoldering up to 135 percent moisture content (McMahon et al. 1980 in Frandsen 1987).

Wet pocosin muck does not burn, but once the water table has lowered, these soils can ignite and sustain combustion. However, the moisture limits for ignition are not known (Frandsen 1993). Research is presently being conducted to determine factors affecting consumption in pocosin organic muck (Frandsen et al. 1993).

b. Surface fuel consumption. Heat generated by consumption of surface fuels can dry, preheat, and then ignite the duff layer. The amount of consumption of large diameter fuels was related to duff reduction and mineral soil exposure in north Idaho (Brown et al. (1991), and western Oregon and Washington (Little et al. 1986; Ottmar et al. 1990, Sandberg 1980).

c. Preburn duff depth. Duff consumption was strongly related to preburn duff depth in the northern Rocky Mountains (Brown et al. (1991); in jackpine (Stocks 1989 in ibid.); Alaska black spruce (Dyrness and Norum 1983); white spruce/subalpine fir (Blackhall and Auclair 1982 in ibid.); and southwestern ponderosa pine (Harrington 1987), but not in deeper duff layers of the Pacific Northwest (Sandberg 1980; Little et al. 1986). **d. Inorganic content.** Mineral soil becomes mixed with soil organic layers by freeze-thaw cycles, insect and small animal activity, overland flow, windthrow, and management actions, particularly skidding of logs (Hartford 1989). Mineral material affects combustion of organic layers because it absorbs some of the heat that would otherwise preheat combustible materials (Frandsen 1987). The greater the amount of mineral material in the organic layer, the lower the moisture content of the organic layer had to be before it would burn (ibid.). If the ratio of mineral particles to organic matter (mass ratio) was greater than about 4 to 1, smoldering did not occur (ibid.).

e. Phase of combustion. Almost all consumption of duff and organic soils occurs during the smoldering and glowing phases of combustion. Combustion can continue for hours, days, and in the case of pocosin soils, for weeks after ignition, if organic layers are dry (Frandsen 1993).

4. Dead Fuel Moisture. Fuel moisture has a significant effect on fuel availability and fuel consumption because it suppresses combustion. Part of the heat produced by the combustion of wood is used to drive off moisture in adjacent woody fuel. If the moisture content is high, the heat generated may be insufficient to dry these fuels and heat them to ignition temperature, and the fire will not continue to burn.

Fuel moisture is the ratio of the weight of moisture in the fuel to that of the dry weight of the fuel. The formula for fuel moisture and its effect on fire behavior is described in Chapter II.B.4.b.(2), this Guide. Moisture effects on woody fuel consumption were discussed in B.2 a. (5), this Chapter, and on duff and organic consumption in B.3.a. The following discussion describes the most important factors affecting moisture content of dead woody fuels, litter layers, and duff and organic layers. Live fuels and their moisture cycles are discussed in B.5., this Chapter.

a. Wetting and drying process. Water in fuels can be present in liquid or vapor form.

(1) Liquid water. Liquid water comes from rainfall, snowmelt, or condensation. It can be present both on the surface, and within cell cavities (Schroeder and Buck 1970). At the fiber saturation point (about 30 to 35 percent of the fuel dry weight), the cell wall holds as much water as it physically can, but no liquid water is present within cell cavities (McCammon 1976).

Liquid water is readily absorbed by fuels through their surface, filling cell cavities and intracellular spaces (Schroeder and Buck 1970). In liquid water, molecules travel with different speeds and directions. A water molecule at or near the surface of a layer of water can attain a high enough speed after colliding with another molecule to escape from the liquid water into the air. By this process, called evaporation, a liquid water molecule becomes a water vapor molecule (ibid.). Evaporation is the primary drying process when fuels are saturated. It decreases in importance as fuels dry below the fiber saturation point.

(2) Water vapor. The following discussion is derived from Schroeder and Buck (1970), except where noted. Water present in the atmosphere in the form of a gas is called water vapor. That part of the atmospheric pressure due to the presence of water vapor is called vapor pressure. The maximum amount of vapor that the atmosphere can hold when it is saturated depends on the air temperature. Water vapor molecules move from an area of higher concentration to one with lower concentration until vapor pressure is equal.

Water molecules in fuels can be bound to cellulose molecules or held by capillary action in tiny openings in the cell wall (Simard 1968). Molecules closest to the cell walls are held the most tightly. Successive layers of water molecules are held with progressively weaker bonds until the cell walls become saturated. At less than saturation, water vapor moves between a fuel particle and the atmosphere if the vapor pressure of the layer of water in the fuel does not equal the vapor pressure of the atmosphere. If the vapor pressure within the outer layer of fuel is greater than that of the atmosphere, moisture escapes to the atmosphere, and fuel moisture content decreases. If the vapor pressure of the atmosphere is greater than the vapor pressure within the outer layer of fuel, the fuel takes water vapor from the atmosphere, increasing the fuel moisture content.

b. Equilibrium moisture content. Equilibrium moisture content (EMC) is the "value that the actual moisture content approaches if the fuel is exposed to constant atmospheric conditions of temperature and relative humidity for an infinite length of time" (Schroeder and Buck 1970). The EMC determines the amount of water vapor that a specific piece of wood can hold (Simard 1968). A unique EMC exists for each combination of atmospheric temperature and relative humidity, with the associated vapor pressure (Schroeder and Buck 1970). If fuel moisture content is greater than EMC, vapor diffuses out of the fuel, and the fuel becomes drier. If fuel moisture content is less than the EMC, water vapor transfers into the fuel particle and the fuel becomes wetter.

Atmospheric temperature and relative humidity are never constant and tend to vary diurnally. Equilibrium moisture content also varies. Because fuels usually take up and release moisture at a slower rate than the temperature and humidity changes, the actual fuel moisture content lags behind the equilibrium moisture content. The greater the difference between the equilibrium moisture content and the fuel moisture content, the more rapidly vapor diffusion occurs, and the more rapidly the fuel particle exchanges moisture with the atmosphere. As a particle approaches equilibrium moisture content, the exchange occurs more slowly. Fuel moisture content never reaches equilibrium moisture content, because other physical processes prevent a complete exchange of vapor (Schroeder and Buck 1970). A fuel that is gaining moisture stabilizes at a lower moisture content than a fuel that is drying (Simard 1968). Van Wagner (1987 in Viney 1991) noted a 2 percent lower EMC for wetting fuels compared to drying fuels.

c. Timelag theory.

(1) Timelag principle. Drying and wetting of unsaturated dead woody fuel has been described by the timelag principle. A timelag has been defined as the length of time required for a fuel particle to reach approximately 63 percent of the difference between the initial moisture content and the equilibrium moisture content.(1)

(2) Timelag period. Under standard conditions, defined as 80 F. and 20 percent relative humidity, the length of time that it takes a fuel particle to reach 63 percent of EMC is a property of the fuel and is referred to as the timelag period (Schroeder and Buck 1970).

(3) Timelag classification. The proportion of a fuel particle exposed to weather elements is mathematically related to its size. Small diameter fuel particles have large surface area to volume ratios. Moisture levels in these fine fuels can change rapidly with changes in temperature and relative humidity. Large diameter fuel particles have small surface area to volume ratios, and their moisture content changes very slowly in response to changes in temperature and relative humidity. Time lag thus increases with increasing fuel diameter.

(a) Dead woody fuel timelag classes. Downed dead woody fuels have been grouped into size classes that reflect the rate at which they can respond to changes in atmospheric conditions (Lancaster 1970). The classes relate to an idealized surface area to volume ratio and an average timelag that represents each fuel class. Classes relate to the theoretical length of time required to reach 63 percent of EMC.

i. 1-hour timelag fuels - less than 1/4-inch diameter (less than 0.6 cm).

ii. 10-hour timelag fuels - between 1/4-inch and 1-inch diameter (0.6 to

2.5 cm).

iii. 100-hour timelag fuels - between 1-inch and 3 inches diameter (2.5 to 7.6 cm).

iv. 1000-hour timelag fuels - between 3 and 8 inches (7.6 to 20.3 cm) diameter.

(b) Forest floor timelag classes. There is a loose correspondence between these timelag classes and forest floor litter and duff, although the deeper the duff layer, the more approximate is the relationship. The corresponding classes assigned for fire danger rating purposes were (Deeming et al. 1977):

i. 1-hour timelag fuels - dead herbaceous plants and uppermost layer of forest floor litter.

ii. 10-hour timelag fuels - layer of litter extending from just below the surface to 3/4 of an inch below the surface.

iii. 100-hour timelag fuels - forest floor from 3/4 inch to 4 inches below the surface.

iv. 1000-hour timelag fuels - forest floor layer deeper than 4 inches below the surface.

(4) Timelag of other fine fuels. Weathered aspen leaves, tree lichen *(Alectoria jubata)* and some cheatgrass fuel beds were shown to act as

1-hour timelag fuels (Anderson 1990). The surface layer of lichens and mosses that carries fire in Alaska responds as a 1-hour fuel to temperature/relative humidity changes (Mutch and Gastineau 1970). However, conifer needle litter of some species belongs in the 10-hour timelag category (Anderson 1990), despite its high surface area to volume ratio. Other factors such as surface covering influence the rate at which fuel moisture changes in response to environmental conditions.

d. Fuel properties that affect dead fuel moisture content.

(1) Surface covering. The presence of a surface coating of organic material can limit movement of water, whether liquid or vapor (Simard and Main 1982). Dead woody fuel with bark gained and lost moisture at two-thirds the rate of the same diameter fuels without bark (Simard et al. 1984).

Moisture exchange in recently cast conifer needle litter is inhibited by a coating of fat, waxes, and cutin deposits (Anderson 1990). Anderson (ibid.) noted timelags of 5 to 34 hours for recently cast conifer needle litter, rather than the expected timelag of 10 hours. Weathering causes the breakdown and removal of needle coatings that slow vapor transfer. Timelags of 2 to 14 hours were measured in weathered conifer litter, which is still slower than the timelag of less than two hours expected for that diameter of particle (ibid.).

(2) Composition. The material of which a fuel is composed affects its structure, porosity, ability to gain or lose atmospheric moisture, and the movement of vapor within the particle. Composition and fuel moisture response properties vary significantly among dead woody fuels, deciduous leaf litter, grass litter, and coniferous needle litter (Simard and Main 1982).

(3) Amount of decomposition. Woody fuels that have been affected by weathering and decomposition often develop deep cracks that increase their surface area to volume ratio. Both liquid water and vapor can enter or leave the fuel through these splits in the wood, increasing the rate of moisture exchange. There may be few naturally occurring forest fuels that are actually 1000 hour timelag fuels, because almost all large pieces of wood have cracks that effectively increase their wetting and drying rates (Miller 1988, personal observation).

The cell structure in highly decomposed wood, such as rotten logs, has broken down, and moisture can travel more easily through this material than through solid wood. The moisture content of rotten wood can be very different from that of sound wood of the same diameter.

(4) Thickness and density of litter or duff layer. Because litter and duff layers have porosities of 70 to 90 percent, air can diffuse through them at 60 to 80 percent of the diffusion rate in free air (Fosberg 1975). The particles of organic matter in these layers exchange moisture with the atmosphere in the void space in the litter and duff layer (ibid). The moisture within the voids seeks equilibrium with the external atmosphere (ibid.). Van Wagner (1979) observed that the drying environment within a 3 centimeter (1.2 inches) deep needle litter layer was less favorable at the bottom than at the top because the lower part of the layer was farther from the drying surface. Anderson (1990) noted that moisture diffusion rates were slower if litter fuel beds were deeper or more densely packed. The lower part of a litter and/or duff layer can become matted and tightly bound by fungal strands (Harrington and Sackett 1990). The wetting and drying response of this layer is likely to be slower than that of the more loosely packed material nearer the surface because of slower rates of water vapor diffusion.

e. Soil moisture effects on fuel moisture content. Afternoon moisture content of eucalyptus *(Eucalyptus spp.)* leaf litter placed on wet soils was much higher than litter placed on dry soils (Hatton et al. (1988). Moisture appeared to diffuse upwards from the wet soil, increasing the relative humidity environment of the leaf litter, causing higher litter moisture content (ibid.). The biggest effect of the wet soil was noted in early mornings, probably because wet soils made more moisture available to condense on dead leaves. Litter on the dry soils was dry enough for the litter to burn throughout the night, while litter on wet soil plots was too wet to burn.

Active surface fire behavior occurred throughout many night time burning periods during the 1988 fire season in Yellowstone National Park. Night time moisture recovery of lodgepole pine litter was much slower and reached lower maximum levels than expected (Hartford and Rothermel 1991). The limited amount of surface litter moisture recovery was partially attributed to the lack of moisture in the air and in the soil that could contribute to an increase in night time litter moisture content (ibid.).(2)

f. Effect of weather factors on fuel moisture content.

(1) Precipitation duration. Wood absorbs water as long as the surface is wet, so precipitation duration is usually more important than precipitation amount in determining moisture content of dead woody fuels (Fosberg 1971 in Simard and Main 1982). The rate of diffusion of liquid water into wood is usually less than the rate at which precipitation occurs, so much of the rain water drips off before it can soak into the wood.

(2) Precipitation amount. The amount of precipitation is more important than the duration of precipitation in determining the moisture content of duff, organic soils, and accumulations of organic materials that occur beneath isolated trees and shrubs. Duff layers and organic soils retain much of the precipitation that falls, allowing it to slowly soak into the fuel particles (Simard 1968 in Simard and Main 1982).

(3) Temperature. Temperature affects both the humidity of the air and its vapor pressure, and thus the equilibrium moisture content. Higher fuel temperatures decrease relative humidity in the microclimate near the ground (Rothermel et al. 1986), which also decreases the EMC. Higher fuel temperatures increase the tendency of bound water vapor to diffuse away from the fuel, thus drying it further (Schroeder and Buck 1970). Fuel temperature is affected by slope, aspect, time of day, cloud cover, canopy cover, sun angle, and the albedo of the fuel.

(4) Relative humidity. Relative humidity has a significant effect on moisture content of small diameter fuels because water vapor can readily penetrate into or escape from the center of small fuel particles. Diurnal changes in relative humidity have little effect on the moisture content of large diameter fuels because their large volume prevents rapid movement of moisture molecules between the surface of the fuel and its center. Relative humidity can have a major effect on large fuel moisture content if there is a long period of time without precipitation.

(5) Wind. Wind has its most important drying effect on woody fuels when liquid water is evaporating because it removes any layer of water vapor that may be adjacent to the fuel. Wind has a greater effect on wet fuel particles that are above the surface, causing them to dry more rapidly than material on the ground (Simard and Main 1982). When fuel is below the fiber saturation point and most vapor loss is by diffusion, the effect of wind becomes less important as the fuel becomes drier

(Schroeder and Buck 1970). Wind has a more significant drying effect on small diameter fuels than on large diameter fuels, duff, or organic layers.

g. Relationship of topography to fuel moisture content.

(1) Fuel moisture tends to vary with topographic position. Fuels are less directly exposed to sun on north slopes than south slopes so their moisture content tends to be higher. Temperatures are generally cooler and humidities higher at upper elevations, so fuel moistures are usually higher than at lower elevations.

(2) Topography partially determines the strength of any night time inversion layer that forms. If a steep inversion and temperature gradient forms, fuel moisture recovery can be fairly high because of low temperatures and high relative humidities.

If an inversion forms in a valley, a thermal belt may form at the top of the inversion layer. In this belt, temperatures are warmer than at lower elevations within the inversion, and warmer than at higher elevations because temperature decreases with altitude. Higher night time temperatures, lower relative humidities, and lower fuel moistures occur within the thermal belt than at other locations along the slope. Fires can remain active throughout the night within the thermal belt, while activity is limited below the inversion layer (Schroeder and Buck 1970).

5. Live Fuel Moisture.

a. Effect of live fuel moisture on fire. Live fuels can either be a heat sink or a heat source in a wildland fire, depending on their moisture content. If live fuel moisture levels are high enough, they absorb some of the heat produced by associated burning fuels without themselves igniting, and thus do not contribute to the progress of the fire. If live fuel moisture is low, the combustion of dead fuels readily produces enough heat to desiccate and ignite the live fuels, which then add to the total amount of heat released by the fire (Burgan and Rothermel 1984). Live fuels can thus retard, stop, or contribute to fire spread.

b. Factors regulating live fuel moisture.

(1) Internal factors. Moisture content of living plants is controlled largely by species morphology and physiology. The amount of water in plant tissue, and thus its moisture content, relates closely to events during a plant's seasonal growth cycle (plant phenology). For a given species, the maximum and minimum moisture content values and the average values during different parts of the growing season are controlled more closely by the plant structure and its adaptations to the general climate of the area, than by daily weather. Seasonal timing of drying for specific deciduous shrub, forb, and grass species were found to be similar between wet and dry growing seasons, although moisture levels were generally higher in the wet season (Brown et al. 1989).

(2) Site factors. Site conditions can cause differences in moisture content within the same species, possibly because of physiological conditioning or even a genetic adaptation to the site (Reifsnyder 1961). Differences in foliar moisture content within a single species were related both to differences in substrate and the amount of shading provided by a forest canopy (Blackmarr and Flanner 1968).

(3) Climatic variation. Climate affects such factors as the timing and length of the growing season, the length of the green-up period, and the existence of seasonal periods of cold- induced dormancy or drought or heat-induced quiescence.

c. Differences among species groups. There are characteristic differences in seasonal moisture patterns for groups of species. Deciduous leaved woody plants tend to have higher moisture content values than evergreen leaved plants, and the seasonal pattern of moisture changes tends to vary more. Coniferous trees have entirely different foliar moisture patterns than deciduous trees. Herbaceous species moisture levels can be higher or lower than that of associated shrubs, depending on the species present and the time of year. There are differences in average maximum and minimum moisture values among species within any group, depending upon the morphology of the species, and the relative amount of new and old growth on the plant.

d. Deciduous leaved shrubs. The general pattern for deciduous leaved shrubs is for moisture to rapidly increase to a peak level soon after bud break and begin to decrease after all new seasonal growth has occurred. Moisture then slowly declines for the remaining part of the growing season until leaves cure.

Data from Alaskan aspen stands illustrate variation in moisture content levels among deciduous species, as well as variability due to site differences (Norum and Miller 1981). Maximum spring moisture content of leaves and small twigs of highbush cranberry *(Viburnum edule)* (Illustration III-1, page III-24) was about 325 percent, but its moisture content dropped to about 225 percent by midsummer where it remained for most of the growing season. Rose *(Rosa acicularis)* on that same site in that same season had a spring maximum value near 375 percent, but its moisture content decreased to about 175 percent where it remained until fall curing. Maximum moisture levels for that same species of rose on a drier aspen site were less than 250 percent and persisted at about 165% for much of the growing season. Blueberry *(Vaccinium uliginosum)* (Illustration III-2, page III-25), a smaller stature deciduous species on a black spruce site nearby, had spring maximum moisture value of less than 250 percent and spent most of the summer at about 125 percent moisture content (Norum and Miller 1981).

For all of these species, moisture content did not significantly decrease as fall coloration appeared on the leaves. Moisture content began to drop markedly as the abscission layer formed at the bases of the petioles and cut off water transport to leaves, when obvious drying and browning of the leaves occurred (Miller 1981).

e. Evergreen leaved shrubs. The general pattern for broad-leaved evergreen shrubs is more complex than for deciduous species because evergreen shrubs sometimes retain old leaves for several years. They tend to have lower spring maximum values and much lower growing season average values than deciduous species. Values increase from an overwintering minima as new growth is added in the spring, or at other times of the year when precipitation triggers growth after a dry season. Values decrease significantly after new growth ceases. Some evergreen leaved species develop ephemeral leaves in late winter and early spring. Average foliar moisture content drops significantly as these seasonal leaves cure and drop from the shrub.

A typical profile for sagebrush *(Artemisia tridentata)* moisture content would be a rise from early to late spring from about 150 percent to about 250 percent, with a subsequent decline to 60 percent or less in mid to late summer (Schmidt 1992). Riedel and Petersburg (1989) found that the lowest summer levels for sagebrush moisture (Illustration III-3, page III-26) were reached one month earlier in one year than the previous summer. Sagebrush flammability has been related to threshold levels of moisture content. (See II.C.2., this Guide.)

In the Alaskan interior, maximum foliar moisture content levels for Labrador tea *(Ledum decumbens)* were only 145 percent, and that peak value occurred about a month after the maximum moisture values were reached in associated deciduous shrub species (Norum and Miller 1981). Moisture content of new leaves of chamise *(Adenostoma fasciculatum)* in California were at 125 percent in late May, dropped to about 60 percent in early September, and rose to about 90 percent when the plants again became physiologically active in early December (Dell and Philpot 1965). Maximum moisture levels for galberry foliage *(Ilex glabra)* averaged about 140 percent in North Carolina, while minimum values were about 100 percent (Wendel and Story 1962). Maximum values for redbay *(Persea borbonia)* foliage were about 120 percent, while fall and winter minima were around 60 percent (ibid.).

f. Herbaceous plants. Herbaceous moisture content can also vary significantly among species. Moisture levels can be much higher at the beginning of the growing season than for other species groups because all of the plant is new tissue. Also, because there is no residual material, all of the plant can become cured, sometimes before the end of the growing season. This is especially notable for grasses and other species in areas with hot, dry summer weather. In north Idaho, moisture content of cheatgrass *(Bromus tectorum)*, an annual grass, for example, was measured to be 150 percent on June 20, but was only 9 percent on July 20 (Richards 1940). All of the plant material, once cured, responds to atmospheric conditions as a dead fine fuel, as reflected by the 9 percent moisture level just cited.

Some species of grasses and forbs in some regions can produce new growth in the fall, after a summer of quiescence, thus causing fall green-up and associated increase in moisture content. Green-up is caused by renewed growth of perennial species and germination of seeds.

Some herbaceous species do not cure and dry out during the summer, rather only begin a significant amount of curing as frost occurs in the fall. In north Idaho, moisture content of fireweed *(Epilobium angustifolium)* plants was 426 percent on June 20 and 241 percent on September 10 (ibid.). In interior Alaska, bluejoint reedgrass *(Calamagrostis canadensis)* was first measured at about 400 percent moisture content on May 27 when the plants had about 1 to 1-1/2 feet of leaf growth. Moisture content of plants declined to about 260 percent by June 30 and was about 200 percent on August 28, just before the first frost (Norum and Miller 1981). In north central Michigan, large leaved aster *(Aster macrophyllus)* was measured at about 420 percent moisture content at the beginning of June, and the lowest moisture level observed for the rest of the summer fluctuated around 300 percent (Loomis and Blank 1981).

Data for most herbaceous species show only a slow decrease in moisture levels after early growing season maxima. However, in western Wyoming, grasses and forbs had some increase in moisture content in response to mid-summer rain. By September, however, the drying trend was not altered by rainfall (Brown et al. 1989).

g. Coniferous trees. Moisture content of coniferous foliage also varies significantly with season but the pattern is quite different than that shown by deciduous and herbaceous species. Coniferous species retain their needles for several years; the number of years is a species characteristic.(3) For most species, the lowest level of moisture content of needles formed in previous years occurs in late spring, during about the same time period in which buds expand, and new needles and twigs are formed. Moisture content of old needles increases during most of the growing season to a maxima during late summer and/or early fall (depending on species and region).

Moisture content of new needles is very high as buds break, needles grow, and stems elongate, but starts dropping significantly about the same time as the new terminal bud on the end of the current year's growth forms. The moisture content of new foliage drops to about the same level as that of old foliage late in the growing season. In the southeastern U.S., conifers may flush more than once during the growing season. The moisture cycle in older foliage may be different from that of conifers that grow in climates with winter cold and/or shorter growing seasons.

The difference between low and high moisture values for 1-year-old black spruce *(Picea mariana)* foliage in Alaska varied from 28 to 40 percentage points on different collection sites (Norum and Miller unpublished). Seasonal lows occurred in June and seasonal high values in August (Illustration III-4, page III-27). Seasonal low values for Douglas-fir foliage occurred in mid to late June in Montana, with a peak value reached by early September (Philpot and Mutch 1971; Rothermel 1980). The range between high and low values varied from about 20 to 40 percentage points.

Crown fires were much more prevalent in Douglas fir trees burning in late spring and early summer experimental fires than on those sites burned in late summer and early fall (Norum 1975). Low springtime foliar moisture values may explain the observed difference. The peak of the fire season in boreal latitudes is usually shortly after summer solstice, and the low foliar moisture content of black spruce may be a factor in tree crown ignition. However, the fire season in the western United States generally peaks in August, at a time when moisture content of conifers is increasing to a seasonal high. The readiness of western species of conifers to crown during extreme fire weather is not due to low foliar moisture values, although it may be enhanced by early drying of the oldest needles.

Measured moisture content of live foliage in northeast Oregon, southwest Idaho (Miller 1988), and northwest Wyoming (Hartford and Rothermel 1991) in the extreme fire season of 1988 was not different from normal moisture values for that time of the year. Experimental evidence suggests that conifers can rapidly transport water into their foliage when heated to temperatures that occur in a wildland fire (Cohen et al. 1990). This can delay branch and foliage drying and could inhibit crown heating and ignition. During drought conditions, trees may not be able to transport water into their crowns, increasing their flammability and hence their crowning potential (ibid.).

6. Fuel Succession. Vegetative biomass tends to accumulate over time. However, not all biomass is available fuel. Biomass is all of the vegetation on a site, while available fuel is what can burn. Fuel succession is the change in the fuel complex over the long term, including changes in loading, size distribution, availability, and live to dead ratios. These changes are the net result of the counteracting processes of accumulation and depletion (Brown 1987).

a. Accumulation.

(1) Litter layer. The amount of foliage that is produced each year affects the amount of new litter that accumulates. Because coniferous trees retain their needles for several years, there may be no relationship between the productivity in a particular year and the amount of needle litter added to the surface fuel layer.

(2) Dead woody fuels. Insects, disease, suppression of individual trees in young stands, and death of lower branches of trees can provide a source of dead woody fuels. These events, and the timing of the addition of the fuels, occur irregularly, as branch material is broken or entire trees fall because of wind, and heavy snowfalls (Brown 1975). Fire can kill trees and shrubs, and whatever woody material is not consumed can become surface dead woody fuels.

(3) Duff and organic layers. Material is added to these organic layers as the lower part of the litter layer, and moss and lichen layer, decompose. Rotten woody material is gradually incorporated into the forest floor, and becomes part of the duff layer.

(4) Live fuels. Shrubs, herbaceous plants, and young conifers can establish and/or increase in volume. Branches die, and increase the flammability of trees and shrubs.

b. Depletion.

(1) Litter. Dead plant material can oxidize and essentially disappear during one growing season. It can remain into the next growing season, be compacted beneath additional litter, and decompose enough to become part of the duff layer.

(2) Dead woody fuels. Dead woody fuels physically deteriorate and settle over time, and compactness increases as supporting branches decay (Brown 1975). A more compact fuel bed is less well aerated, and may dry more slowly, have a higher moisture content, and be a more favorable environment for additional decomposition.

(3) Live fuels. Productivity of an understory layer of shrubs and herbaceous plants can decrease significantly as the canopy closes, resulting in a much lower annual addition of litter. A coniferous fuel ladder can grow tall enough that its lower branches no longer provide a bridge between surface and crown fuels.

c. Patterns of fuel succession.

(1) Forests. The generality that downed woody fuels accumulate over time is, in many cases, not true (Brown and See 1981). The amount of forest fuel depends on stand history, whether the stand was visited by insects, disease, wind, and fire, and at what intervals. The size and pattern of disturbance, and amount of fuel that results, can vary with the event, and tree and branch mortality can be compounded by drought. Agee (1993) also relates the amount of forest fuel to stand disturbance. Changes in the amount of fine and coarse woody fuels over time relate to the amount of biomass present before a disturbance, the severity of the disturbance, and successional patterns after the stand is disturbed (ibid.).

(a) Relationship to stand disturbance. When a wildland fire occurs in a forested stand, the severity of the impact on the stand, and resulting amount of surface fuels and rate of their accumulation, can vary (Muraro 1971 in Brown 1975). For example, if a fire occurs in a lodgepole pine stand that burns only in surface litter layers, it can kill or weaken many of the trees but not consume much of the foliage. Surface fuels increase moderately as trees die and fall. A fire in a lodgepole pine stand that burns into the duff layer can consume many structural tree roots. This makes trees susceptible to rapid blowdown, and fine fuels are added to the stand at a much higher rate than after a lower severity fire. A high intensity crownfire in a lodgepole pine stand can burn off many of the fine branches in the tree crowns. If it also burns deeply into the duff layer, most of the trees will fall fairly quickly. Most of the fuel added would be large diameter material. Because downed trees are not supported by small diameter branchwood, they would come into contact with forest floor sooner and decompose more readily.

Whether the young stand of lodgepole pine that establishes after fire has a low or high dead fuel loading also depends on the frequency of fire. The stand that develops after a fire that caused rapid blowdown of trees with a lot of branchwood would have a high loading of dead fuel in all size classes. If a fire occurs in this young stand of trees, much of the crown-stored seed could be destroyed and most of the fuel consumed. A sparse stand of lodgepole pine could subsequently establish that has a much lower loading of dead woody fuel than the previous stand (Muraro 1971 in Brown 1975).

(b) Varying patterns among live and dead fuels. Fuel succession is more complicated if live and dead fuels are involved (Brown and See 1981). There may be an increase in one class of fuel while another is decreasing or becoming unavailable. Dead woody fuel may decompose while an understory of trees establishes. The loading of dead woody fuel may increase while some trees become tall enough to be much less available to surface fire (Brown and See 1981). Early successional herbs, such as bracken fern in western Oregon, can cause a high loading of fine fuels before the canopy closes and shades out these plants (Isaac 1940 in Agee 1993).

(c) Relationship to stand age. There is no clear relationship in the northern Rockies (Brown and See 1981) between stand age and amount of dead woody material. The amount of fuel in young and mature forests cannot be related to age because too many other factors are involved. The only generalities are that downed woody fuel loadings tend to become predictably high as stands acquire old growth characteristics, but loading is unpredictable from age alone in young, immature, and mature stands (ibid.).

In western Oregon and Washington, stand replacing fires generally occur at much longer intervals than they do in the northern Rocky Mountains. Fuels in the 0 to 3-inch (to 7.6 cm) range are usually at their highest levels in early stages of postfire succession (Agee 1993). 1000-hour fuel biomass is highest in mid-successional stages when some stems die because of naturally occurring self-thinning. Biomass of larger logs is greatest in the oldest stands.

(d) Relationship to site productivity. Fuel loading and site productivity are not well correlated (Brown and See 1981). In warm, moist forest types, productivity is fairly high, but fuel may not accumulate because the decomposition rate keeps up with fuel production (ibid.). In cool, dry forest types, productivity tends to be low, but a relatively higher proportion of biomass may accumulate as fuel because decomposition is limited (ibid.).

(e) Relationship to fire exclusion. In many areas of the western U.S., naturally occurring fires used to occur at a fairly high frequency. With the onset of organized fire suppression activities, and the removal of fine fuels by livestock grazing, wildland fires became an infrequent event in many forest types. If fire exclusion has removed several fire cycles from a forested stand, the ecological effect is much more profound than if fire has only been effectively suppressed for one-third of the length of a stand's natural fire rotation. In parts of the southwestern U.S., for example, the exclusion of fire from ponderosa pine stands that previously burned at intervals ranging from 2 to 10 years has resulted in higher loadings of litter, forest floor duff, and in some cases, down dead woody fuels (Harrington and Sackett 1990). While the amount of fuel may not be predictable from age, it is logical to conclude that there is more fuel in stands without understory fire for 80 to 100 years than if underburns had continued to occur at frequent intervals.

(2) Shrublands.

(a) Sagebrush. The percentage of dead stemwood in sagebrush *(Artemisia tridentata)* plants increases with age. However, when modelling the effect of higher proportions of dead branchwood on fire behavior, only a small increase was found (Brown 1982). The total amount of fuel correlates to the height of the stand, but stand height does not correlate well with age (ibid.). The amount of fuel in older stands of sagebrush is greater if the volume and density of shrubs has increased.

(b) Chaparral. Old stands of chaparral have been observed to be more flammable than young stands, and this difference has been attributed to an increasing proportion of dead branch material in older age classes of shrubs (Paysen and Cohen 1990). No correlation was found between the percentage of dead branch material and age of chamise in southern California (ibid.).

Because all leaves and fine branch material in the chaparral canopy tends to be consumed by fire when foliar moisture content is low, a stand with more leaves and twigs has more fuel. For any given site, the amount of biomass tends to increase with age of the stand, and it may be this increase in total biomass that causes the higher flammability observed in old stands. However, because of variability in site productivity and species composition, it cannot be said that every stand of chaparral of a certain age is more flammable than a stand that is younger.

C. Resource Management Considerations

The primary ways to manipulate fire effects on fuels are to modify fuel availability and to change the way an area is ignited and burned.

1. Fuel Availability.

a. Fuel moisture.

(1) Change the prescribed fuel moisture. When planning a prescribed fire, the moisture contents specified in the prescription can be chosen to achieve selected effects on fuels.

(a) Fine fuel moisture. Fine fuel moisture indirectly affects overall fuel consumption by determining which fuels ignite. Fine fuel moisture is defined by specifying different ranges of temperature and relative humidity in the prescription.

(b) Large fuel moisture. In forested areas, the moisture content of large diameter woody fuels is the chief factor affecting the amount of total consumption. Remember that rotten woody material can burn at a much higher moisture content than sound material of an equivalent size.

(c) Duff and organic layers. Consumption of soil organic material is also directly related to its moisture content (Brown et al. 1985).

i. At moisture content greater than about 120 percent, duff will not burn.

ii. At moisture content less than about 30 percent, duff will sustain combustion on its own once ignited.

iii. The amount of consumption of duff between 30 and 120 percent moisture content depends on the amount of consumption of associated fuels. **(d)** Live fuels. By prescribing the moisture content of live fuels in the surface fuel layer, the amount of their flammability and consumption is regulated. The amount of scorching of a conifer canopy may be greater early in the growing season when trees are just becoming physiologically active and foliar moisture content is lower than it is later in the year. Live fuels may be consumed, regardless of their moisture content, if a large loading of dry, dead woody material burns.

(2) Alter the fuel moisture. Use of water or foam changes the moisture and burning characteristics of fuel. These techniques are commonly used to build fireline and protect specific features, such as wildlife trees.

b. Fuel loading and distribution.

(1) Remove the fuels. Less fuel is available, and there is less potential for heat release, if fuels are removed from a site. Fuels can be removed by:

(a) Grazing.

(b) Commercial thinning of forests.

(c) Firewood sales.

(d) Yarding unmerchantable material to a central location during forest harvesting operations.

(2) Change the fuels. If fuel distribution or arrangement is changed, flammability, and the potential for heating, changes.

(a) Crushing. Crushing fuels increases fuel bulk density and can make the rate of burning slower. However, if crushing compacts fuels to a more ideal arrangement, it may enhance combustion.

(b) Lopping and scattering. Cutting and scattering of branches during a logging or thinning operation makes fuel continuity more uniform, but also decreases the potential for concentrated heating where piles of branches would have been located.

(c) Piling or windrowing. Piling or windrowing fuels breaks up the continuity and decreases the likelihood that fire can spread. A fire that starts (or is started) in a pile or windrow has a greater potential for subsurface heating if low moisture content of larger pieces and low amounts of intermixed mineral soil permit a high degree of consumption.

(d) Chaining. Chaining woodlands or shrub dominated areas alters the distribution and continuity. If removal of the trees or shrubs allows more grasses and forbs to grow (or if they are seeded), the flammability of the site will be significantly higher because of the presence of downed woody fuels.

(e) Herbicide. The use of herbicide to kill shrubs and woodland trees results in a large amount of standing dead vegetation. Intermixture of newly established grasses and forbs will result in a highly flammable site.

c. Fuel chemistry. Application of long term fire retardants inhibits fuel ignition and hence fuel consumption.

2. Ignition.

a. Backing vs. heading fires. Backing fires usually result in more complete fuel consumption, particularly of litter and duff layers, than heading fires.

b. Mass firing. Use of mass firing techniques, such as center firing or concentric firing, may result in more complete consumption of fuels, for a given moisture regime, than if a backing or heading fire were used.

c. Ignition devices. Use of ignition devices such as a heli-torch that can apply a lot of fire in a short period of time can result in a fire that causes more woody fuel consumption than if surface ignition were used.

D. Methods To Monitor Fire Effects

Fuels inventory data are collected to facilitate accurate prescription development, to determine if fuel consumption objectives are met, and to relate fuel reduction to fire effects on other resources. Fuel moisture data can determine whether prescribed conditions are met, and document the conditions that correlate with specific amounts of fuel consumption and related aspects of the heat regime of the fire. If smoke emissions are a critical factor in a prescribed fire program, both fuel moisture and fuel consumption data can be used to predict emissions, refine prescriptions, and obtain an accurate estimate of the amount of emissions produced by a particular prescribed fire. While mineral soil is not a fuel, soil moisture data can provide important information for documentation and interpretation of fire effects that are related to sub-surface heating.

1. Fuel Loading. The type and amount of fuels inventory should match the objective for

doing the inventory, because fuels data can be expensive and time consuming to collect. Specific techniques have been developed for inventorying or estimating living and dead biomass in forest and rangeland vegetative types, many of which were developed specifically for assessing fuels. The time of year when sampling is performed can be critical if any component of live vegetation is being measured, particularly grasses and forbs. Sampling performed before the full amount of seasonal growth has occurred can produce serious underestimates in fuel loading. Sampling during the normal fire season, or during the specific time of year when a prescribed fire is planned to occur, is recommended. Agency specific guidance for fuels measurement in forests and in grassland and brush is provided in USDI-NPS (1992).

a. Destructive sampling. Destructive sampling is the clipping, sorting by size category, and weighing of all fuel in a representative area. This is an extremely accurate way to collect fuels data but is also time consuming and expensive. All of the other procedures detailed here derive estimates of fuel loading from specific sets of measurements.

b. Estimating weight of herbaceous fuels. There are many techniques for estimation of weight and production of herbaceous rangeland vegetation because of its use as livestock forage. Most techniques for weight estimation can be placed into one of three categories:

1) clipping and weighing, 2) estimation, and 3) a combination of weighing and estimation (Brown et al. 1982). Details on use of these and related methods can be found in Hutchings and Schmautz (1969), and Chambers and Brown (1983).

c. Estimating shrub weight.

1) Rangeland shrubs. Average height of an entire stand of big sagebrush can be estimated by multiplying 0.8 times the average height of the tallest plants in that stand (Brown 1982). Average sagebrush height and percent can be converted to tons/hectare (tons/acre) (ibid.). Martin et al. (1981) developed estimates for average loading by percent of crown cover for big sagebrush, antelope bitterbrush *(Purshia tridentata)*, snowbrush ceanothus *(Ceanothus velutinus)*, and greenleaf manzanita *(Arctostaphylos patula)*.

2) Forest shrubs. Shrub biomass can be estimated from basal stem diameters for 25 species common in the northern Rocky Mountains (Brown et al. 1982).

d. Live/dead ratio. The live/dead ratio within plants can be obtained by ocular estimation or through more time consuming destructive sampling techniques.

e. Inventory of dead woody fuels and duff.

1) Direct measurement. Brown et al. (1982) provides comprehensive procedures for inventorying downed woody material, forest floor litter and duff, herbaceous vegetation, shrubs, and small conifers. Field sampling methods include counting and measuring diameters of downed woody pieces that intersect vertical sampling planes, comparing quantities of litter and herbaceous vegetation against standard plots that are clipped and weighed, tallying shrub stems by basal diameter classes, tallying conifers by height classes, and measuring duff depth (ibid.). All of these procedures can be completed at one sample point in about 15 minutes. The authors recommend that at least 15 to 20 sample points be located in an area where fuel estimates are desired. Although these procedures apply most accurately in the Interior West, techniques for estimating biomass of herbaceous vegetation, litter, and downed woody material apply elsewhere (ibid.).

Formulas for calculating fuel loading from field measurements are found in Brown (1974). Anderson (1978) provides graphs from which loading can be estimated. The calculation procedures are converted into a computer program listed in Brown et al. (1982). Agency fire management staff may have software that can be used to calculate fuel weights from these inventory data.

2) Photo series. A photo series developed for a specific fuel type in a defined geographic area can be used to obtain an estimate of fuels. The stand of interest is compared to pictures of similar stands in which fuel inventories have been conducted. Precision is intermediate when compared to other methods for obtaining fuels information. Photo series are more accurate for assessing fire potential than for estimating fuel loads (Fischer 1981a). Photo guides are available for natural and activity fuels for coastal and interior forest types in the Pacific Northwest (Maxwell and Ward 1976a, 1976b, 1980); for forest residues in two Sierra Nevada conifer types (Maxwell and Ward 1979); for natural fuels in Montana (Fischer 1981b, c, and d); for thinning slash in north Idaho (Koski and Fischer 1979); and for natural forest residues in the southern Cascades and northern Sierra Nevada (Blonski and Schramel 1981).

Supplementary information on fire behavior and resistance to control were compiled for existing photo guides for Pacific Northwest coastal forest (Sandberg and Ward 1981); for two Sierra conifer types (Ward and Sandberg 1981a) and for Northwest ponderosa and lodgepole pine types (Ward and Sandberg 1981b). There are presently no photo series for the Great Basin or southwest U.S. Fischer (1981a) explains how a photo guide is constructed with enough detail for a field office to prepare a series on specific fuel types.

2. Woody Fuel Consumption. Fuel consumption is measured by comparing prefire fuel loading data with data collected after a wildfire or prescribed fire is extinguished. If a quantitative fuel reduction objective was set, and a related fuel inventory technique selected and performed before the fire, that same inventory must be conducted again. Changes in fuel loading can be less precisely estimated by comparing photo series pairs that match the appearance of the site before and after burning.

In some cases, total downed woody fuel increases after a fire because of the addition of branchwood and boles of trees that fell as a result of the fire. If this has occurred, the observation should be recorded with field data, as it will help interpret fuels data when the project is being evaluated.

3. Litter/Duff Reduction. Techniques for measuring litter and duff reduction are described in Chapter II.D.8., this Guide, "Burn Severity/Depth of Burn."

4. Fuel Moisture.

a. What should be sampled. Categories of fuel moisture that can be related to the heat regime of a fire and to fire effects include the following:

- less than 1/4-inch diameter down dead woody fuels (1 hour fuels)

- 1/4 to 1-inch diameter down dead woody fuels (10 hour fuels)

- 1 to 3-inch diameter down dead woody fuels (100 hour fuels)

- 3 to 8-inch diameter sound down dead woody fuel (1000 hour fuels)

- large diameter rotten down dead woody fuel

- surface litter

- thin duff layer

- upper part of a deep duff layer

- lower part of a deep duff layer

- organic soils

- organic layers beneath isolated trees and shrubs

- mineral soil

- tree foliage

- shrub foliage

- herbaceous plants

Moisture data required varies with vegetation type, expected fire behavior and fire characteristics, the fuel situation on the site, and the objectives for conducting the fire. While not a fuel, mineral soil is included in this list because of its role in regulating heat transfer into soil. (See Chapter V.B.1.a, this Guide.)

b. Where fuel moisture should be sampled. The following discussion is derived from Norum and Miller (1984), and Sackett (1981). Fuel moisture samples should be collected within the proposed burn unit and be representative of the area. Samples should span the range of vegetative conditions, fuel conditions, elevation, aspect, and slope on a prescribed fire site, because these variables can lead to notably different fire characteristics and fire effects. Notably wet and dry microsites should be sampled, along with the areas between them. This also applies to shaded and exposed spots, greater and lesser concentrations of fuel, older and younger stands, and any other within-plot variations that might influence fuel moisture content.

If fuels inside and outside of the prescribed fire unit are notably different, as in the case of a clearcut, fuel moisture outside the burn unit should also be monitored and documented. Differences in anticipated fire behavior within and outside of the intended fire area help to determine the probability of a spot starting a fire outside of the unit and the needed contingency suppression forces in case the fire escapes.

c. The number of samples to collect. Prefire variability in moisture content of fuels can be fairly high. Prefire samples can be used to determine how many samples must be collected to guarantee the needed sampling precision. See Chapter XI.B.1., this Handbook, for an example of how to determine how large a sample size is required.

d. Direct sampling. Detailed discussions of fuel moisture sampling methods and drying procedures are given in Norum and Miller (1984) and Countryman and Dean (1979). While these two publications were designed for specific geographic locations, the general principles involved can be applied to other parts of the country.

(1) Containers. Commonly used containers are aluminum soil sample cans, paint cans, nalgene bottles, and wide-mouth glass jars. Plastic bags, even if they have a tight seal, are not suitable for sample collection. Moisture can escape through small pores in the plastic, especially if the sample sits for a while before processing. Moisture from the sample can condense on the bag, and be lost when the sample is transferred to another container for drying. Use of plastic bags for sample collection can result in underestimation of sample moisture content.

(2) General field procedures. Detailed procedures for collecting fuel moisture samples in Alaska were developed by Norum and Miller (1984). The publication contains many general procedures which can be followed in any part of the country. Some general guidelines include:

(a) If recent rain, frost or dew have left obvious moisture on the surface of the plants, sample moisture content may be overestimated.

(b) Material collected from living plants, leaf litter, and upper duff layers becomes fairly stiff as it dries, and may expand, causing it to spring from the sample containers during the drying process. Material must be loosely packed into sample containers. Stems and leaves of live fuels can be cut into small pieces as they are placed in the sample can.

(c) Samples must be kept cool, dry, and out of direct sunlight until they are processed. Countryman and Dean (1979) recommend placing samples within an ice chest until they can be brought back to the lab for processing. Lunch coolers with a container of ice can also be used. If samples cannot be processed immediately, refrigerate them, still sealed, until they can be weighed.

(e) Live fuels. Guidelines for collecting specific species of plants are given in Norum and Miller (1984), and can be adapted to other species. Plant material sampled should consist only of living foliar material, not dead branches, dead leaves, flowers, or fruits. A consistent manner of sampling is most important, both for each species of plant and throughout the growing season. Plant growth stage at the time of sampling should be noted.

(3) Processing samples. A basic requirement for processing of fuel moisture samples is a top-loading beam or torsion balance scale, capable of measuring to 0.1 gram. If many samples must be processed over the course of a field season, or several seasons, the cost of an electronic balance may be justified because of the time saved and accuracy that is gained.

Several different means exist for determining fuel moisture content in the office or lab once samples have been collected.

(a) Xylene distillation. The xylene distillation method is a laboratory procedure which produces extremely precise estimates of moisture content for both live and dead fuels. However, this method is comparatively expensive and takes a significant time to perform. It will not be discussed further here.

(b) Microwave oven. Microwave ovens have been used successfully to dry dead woody fuels (Norum and Fischer, 1980). McCreight (1981) did not recommend use of a microwave oven for drying live fuels.

(c) Computrac®. The Computrac, Model FS-2A is a moisture analyzer that weighs and dries a small sample and provides a moisture content on a dry-weight basis. Material is dried in an automatically controlled oven chamber, continuously weighed, and moisture content calculated.

Results are obtained within about 10 to 20 minutes for dead woody fuels, or about one hour for live fuels. Fuels can be dried at 95 C. (203 F.), minimizing any loss of volatiles.

While quite accurate, a major disadvantage of the Computrac is the very small size of the sample which can be processed, approximately 3 to 10 grams of material. In order to obtain a representative sample, many samples must be subsequently processed. A second major disadvantage of the Computrac is its high purchase price.

(d) Drying ovens. Detailed procedures for use of a scale and drying oven can be found in Countryman and Dean (1979) and Norum and Miller (1984). Processing of fuel moisture samples in a drying oven has long been the standard for measurement of fuel moisture content. Samples are weighed on a scale to the nearest 0.1 gram, dried in the oven, and then weighed again to determine the amount of water lost. Ovens are customarily set to 100 C. (212 F.) for dead woody fuels, and 80 C. (176 F.) for live fuels. The standard drying time is 24 hours. Major advantages of a drying oven are that many samples can be processed simultaneously, and accurate values are obtained if proper procedures are followed. The disadvantage is the 24 hour delay in arriving at the values for moisture content.

e. Fuel moisture meters. Several brands of fuel moisture meters are presently available that provide a direct measurement of fuel moisture. Most meters work by measuring the electrical resistance between two probes which are inserted into a piece of wood. Most of these meters were developed for testing the moisture content of kiln dried lumber and are most accurate at lower moisture values. Some of these probes are calibrated on a wet weight basis, not a dry weight basis, and will not give answers that can be used as input to fire behavior prescriptions. Most of the probes are less than an inch in length and cannot penetrate deeply enough into large diameter wood to measure its moisture content. However, a fairly accurate measurement of large fuel moisture content can be made by cutting across the diameter of a large piece of woody fuel and inserting the probe into the freshly exposed surface. Because meters were developed to measure moisture content of wood, a fairly dense substance, they cannot give an accurate reading of moisture content within litter or duff layers, or of soil. These meters are not suitable for live fuel moisture estimation because the probes cannot be adequately inserted into the live fuels, and most meters do not operate at high moisture contents.

f. Ways to estimate dead fuel moisture content.

(1) Calculation.

(a) Fine fuels. The moisture content of fine dead woody fuels can be estimated with several different computation models. All models use inputs which describe the environment in which the fuel is located, temperature, relative humidity, slope, and time of year. The most simple but marginally accurate calculation method is available in tabular form in the course materials for S-390, Intermediate Fire Behavior, and S-590, Fire Behavior Analyst. A more accurate estimate can be made using the fine fuel moisture model (MOISTURE) in the BEHAVE system. (See XII.C.1.B.)

(b) Large diameter downed fuels. There is a regionally specific model that accurately predicts the moisture content for large diameter dead woody fuels, the ADJ-Th (Adjusted Thousand Hour) model developed by Ottmar and Sandberg (1985). This model applies to 3 to 9-inch diameter Douglas-fir and western hemlock logging slash in western Washington and Oregon.

(2) Fuel sticks. A standard set of fuel moisture indicator sticks consists of four, 1/2 inch diameter ponderosa pine sapwood dowels spaced one-quarter inch apart on two 3/16-inch- diameter hardwood pins. They do not measure any specific fuel but rather "measure the net effect of climatic factors affecting flammability" (Davis 1959). When completely dry, the sticks weigh 100 grams. Their moisture content can be obtained by weighing them, using any of several types of commonly available scales. Procedures for use of fuel sticks are described in detail in Finklin and Fischer (1990).

Fuel sticks have important limitations. The differing density of the wood of which the sticks are made can cause dowels made from the same board to give different fuel moisture values when exposed to the same environment. Response characteristics of the sticks can change significantly with continued exposure and wood aging. A fuel stick should be discarded after one season's use, and more often if rapid weathering or checking has occurred. A fuel stick must be exposed at least five days before moisture readings will be accurate. Because of the variation in fine fuel moisture content caused by microsite differences, use of only one set of fuel sticks to represent moisture conditions for a prescribed fire may give a very inaccurate estimate.

E. Summary

Fuels are an integral part of most wildlands. At some time after death, or while still alive, all vegetation becomes potential fuel. The single most important factor controlling the flammability and consumption of fuels is their moisture content. The moisture content of dead wildland fuels is regulated by environmental factors, while that of living plants is largely controlled by physiological processes. Other fuel properties can also affect the degree of consumption. All direct effects of fire result from the characteristics of the heat regime of the fire, which is controlled by the manner in which fuels burn. Management of fuels is important because by doing so, the heat regime of a fire is also regulated.

1. 0.63 approximates the value 1 minus 1/e, where e is the base for natural logarithms (Schroeder and Buck 1970). This value is used to describe fuel moisture relationships because the shape of the drying and wetting curve as a function of time is approximately logarithmic.

2. The presence of unweathered organic coatings that limited vapor movement in and out of the most recently cast needle litter was another likely cause of the slow moisture response (Hartford and Rothermel 1991).

3. Conifers of the Larix genera (larches and tamarack) have deciduous needles, and their moisture content will not be discussed here.

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CHAPTER IV - AIR QUALITY

By Larry Mahaffey and Melanie Miller

A. Introduction

Wildland fires produce smoke, an air pollutant. Smoke that is a result of human activities is subject to legal restrictions imposed by state, Federal, and local governments. Prescribed fire is a planned event, and Federal land managers have a mandate to manage prescribed fire smoke. Land managers must have a clear understanding of the regulations and processes that must be complied with to manage smoke. The liability for downwind effects is the responsibility of the prescribed fire managers who produced the smoke.

The National Environmental Policy Act (NEPA) is the law that establishes fundamental environmental policy for the U.S. and provides the process for considering the full range of impacts in planning land use activities. Agencies have the responsibility to disclose possible air pollution impacts from land management projects. The Federal land manager is required to conduct NEPA analysis if the project includes a "significant" amount of burning, may have impacts on sensitive vistas or visibility, or is located near a public roadway.

The 1977 Clean Air Act (CAA) mandates the protection of human health and the prevention of significant deterioration of air quality, and establishes acceptable levels of emissions. States are charged with the responsibility for protecting air quality. States write State Implementation Plans (SIPs) to interpret and enforce the Clean Air Act, including the identification of Designated Areas (DA), principal population centers or other areas requiring protection of air quality.

Designated Class I Areas include specific National Parks, Wilderness Areas, and certain Indian reservations. A goal for Federal Class I Areas is to prevent any future impairment of visibility and remedy any existing impairment of visibility that results from human-caused air pollution. The 1990 Amendments to the Clean Air Act specify that individual States must consider smoke from wildland fires in their SIPs. Requirements for prescribed fires can be established by States in the SIP that are more stringent than those in the CAA.

Anyone using prescribed fire must consider smoke management. Smoke management requirements and procedures vary because of the different amounts of fuel burned, fuel type, topography, meteorology, and presence of smoke sensitive areas (Mathews et al. 1985). The following questions can help a manager determine the level of smoke management that is needed, and whether an increased emphasis on smoke management is required.

1. Is the public informed of agency resource objectives for using prescribed fire?

2. Is the amount of acreage treated with prescribed fire predicted to change significantly?

3. Does topography or meteorology cause poor smoke dispersion?

4. Will prescribed fires cause or contribute to increased levels of air pollutants?

5. Will smoke from prescribed fires result in public health and safety problems or complaints?

6. Are Best Available Control Measures (BACM) used to manage prescribed fire smoke?

The effects of smoke on the airshed and the public and the opportunities to reduce these impacts will be discussed in this chapter. Managers have the responsibility to do the best job possible to control and mitigate the impacts of smoke that result from their actions or treatments.

B. Principles and Processes of Fire Effects

1. Combustion Process.

a. Chemistry of combustion. The following is a summary of information provided by Byram (1959). Wood is a chemically complex substance, composed primarily of cellulose and lignin, of which carbon, hydrogen, and oxygen are the primary constituents. When wood burns in a completely efficient manner, it combines with atmospheric oxygen, and produces water, carbon dioxide, and energy. Some of the water that results from combustion is evaporated from the fuel, but a larger proportion is a product of the chemical reaction.

b. Phases of combustion. The four phases of the combustion process are described in Chapter II.B.2, this Guide. Some strategies for smoke management rely on manipulation of the amount of fuel consumed in each combustion phase. The types of emissions and factors regulating their production will be discussed with respect to the phases of combustion. For a more complete discussion of the phases of combustion, see Sandberg et al. (1978).

(1) Pre-ignition phase. During the pre-ignition phase, gases, vapors, tars and charcoal are produced. The proportions and amounts vary widely according to the conditions under which pyrolysis occurs. If rapid heating occurs during pyrolysis, less charcoal, a lot of tar, and highly flammable gases are produced. Slow heating during the pyrolysis process results in the production of more charcoal, little tar, and lower amounts of flammable gases (Sandberg et al. 1978).

(2) Flaming phase. The following is from Ryan and MacMahon (1976 in Sandberg et al. 1978). The principal chemical by-products of flaming combustion are carbon dioxide and water. However, some pyrolyzed substances cool and condense without passing through the flaming zone. Other substances are only partially oxidized as they pass through the flames, and many combustion by products are produced. Low molecular weight organic compounds may remain as gases and are dispersed by wind. Tar droplets and particles of soot result from the cooling and condensation of compounds with higher molecular weights. Visible smoke consists of mostly tar, soot, and water vapor.

(3) Smoldering phase. The lower temperatures of the smoldering phase allow some gases to condense as visible smoke. Smoldering fires produce at least twice the emissions of flaming fires. Heat release is inadequate to loft the smoke as a convection column, so smoke stays near the ground and may persist in relatively high concentrations. Most of the smoke produced consists of tar droplets less than one micron in size (Johansen et al. 1985).

(4) Glowing phase. During the glowing phase, combustion is fairly efficient. Carbon monoxide and carbon dioxide are released, but no visible smoke is formed (ibid.).

c. Combustion efficiency. If combustion of fuels in wildland fires was 100 percent efficient, the burning of one ton of wood would release 3,670 pounds (1,665 kilograms) of carbon dioxide and 1,080 pounds (490 kilograms) of water (Sandberg and Dost 1990). All of the carbon in the fuel would oxidize to carbon dioxide. However, the combustion of fuels in wildland fires is not a completely efficient process. The most important reason for incomplete combustion is that wind cannot deliver enough oxygen to the combustion zone to mix efficiently with all of the flammable gases produced (Ryan and McMahon 1976 in Sandberg et al. 1978). There are differences between heading fires and backing fires in the proportion of time spent in the different combustion phases listed above (ibid.).

(1) Heading fires. A heading fire is one in which the flaming front moves ahead rapidly. The fire may be pushed by the wind, move upslope, or be influenced by both factors. These fires burn with relatively high fireline intensity, moving quickly from one fuel element to another. The main combustion zone moves before most fuel elements are completely consumed by fire. The flames continue ahead, leaving behind a large area of smoldering fuel (ibid.).

(2) Backing fires. A backing fire burns into the wind or downslope. Because the flames move more slowly, a higher proportion of fuel is consumed in the flaming zone of the fire, leaving less fuel to smolder after the flaming front has passed.

(3) Smoke production. For a given fuel bed and set of burning conditions, a heading fire causes more total smoke production than a backing fire. A heading fire generally results in more fuel consumed in the smoldering phase of combustion than does a backing fire, and smoldering fuels produce more smoke than fuels burned in flames. A backing fire is a more efficient fire because more fuel is consumed in flaming combustion, and less smoke production results.

d. Fuel properties that affect smoke production. Fuel properties that affect smoke production are those that influence the phase of combustion in which fuel consumption occurs, and the total amount of fuel consumed. These factors are discussed more completely in Chapter III. Fuels.

(1) Fuel particle size, arrangement, and continuity. The smaller the size of the fuel particle, the more quickly it can ignite and be consumed. The arrangement of fuel particles affects the amount of oxygen that reaches them. More tightly packed fuel, such as a bed of juniper or spruce needles, burns less efficiently, and produces more smoke than a loosely packed fuel bed, such as one of ponderosa pine needles. Fuel continuity is a factor because if fuel particles are too widely spaced, sustained ignitions cannot occur; flames are unable to ignite adjacent fuels.

(2) Fuel loading. A site with large amounts of fuel can generate more smoke than a site with little fuel. The size class distribution of the fuel is also important, because the proportion of fuel in each size class affects the proportion that may be consumed in flaming versus smoldering combustion. Smaller diameter fuels, such as loosely packed grass litter, fine branchwood, and live moss and lichens burn almost entirely in flames with little residual smoldering. In contrast, large diameter downed woody fuels such as those found in logging slash are rarely consumed in flaming combustion, and thus have higher potential to emit large amounts of residual smoke.

(3) Fuel moisture. The moisture content of the different size classes of fuel affects smoke production because it influences fuel availability and combustion temperatures. Extremely dry fuels burn rapidly and completely, while wet fuels burn slowly or not at all. Any moisture released from the fuels absorbs some heat energy from the fire, limiting combustion temperatures (Ryan and McMahon in Sandberg 1978). If larger size classes of fuels have a high moisture content, most or all of the heat released by flames will be expended evaporating water, and little consumption of large diameter fuels occurs. Fuel moisture, its role in combustion, and its relationship to past and present atmospheric conditions, is discussed more completely in Chapter III, Fuels.

2. Emissions. Emission products from fires vary greatly, depending upon the type of fuel, fireline intensity, fuel moisture, wind, and temperature of the fire.

a. Combustion products. Hundreds of different compounds are emitted in the smoke from wildland fires. More than 90 percent of the mass of smoke emitted from wildland fires consists of carbon dioxide and water. Carbon in the fuel is also converted to particulate matter, carbon monoxide, aldehydes, and hydrocarbons, as well as complex organic materials (Johansen et al. 1985). Nitrogen oxides and hydrocarbons produced by the fire can react together in the presence of sunlight and produce ozone and organic oxidants. Ozone production occurs in the top of a smoke plumes where there is more light, and in downwind areas where smoke is less dense (Sandberg and Dost 1990).

Because most of the adverse effects of smoke are related to the amount of smoke produced, fire managers need to know how much smoke is generated. The answer can be estimated from two numerical expressions: emission factor and emission rate.

b. Emission factors. An emission factor is the mass of contaminant emitted to the atmosphere by the burning of a specific mass of fuel, and is expressed in pounds per ton in the English system or grams per kilogram as the metric equivalent (Johansen et al. 1985). An emission factor can be calculated for a single fire, or a single combustion stage of one fire, or it can be a statistical average for a geographical area or a set of similar fires (Sandberg and Dost 1990).

(1) Carbon dioxide. The carbon dioxide emission factor for prescribed fires ranges from 2,200 to 3,500 pounds per ton of fuel consumed (1098 to 1747 g/kg) (Sandberg and Dost 1990). The combination of carbon in the fuel with atmospheric oxygen during combustion results in the production of a greater weight of carbon dioxide than the original weight of the fuel. Carbon dioxide is a "greenhouse gas", i.e., it may have an effect on the global radiation budget and may be a factor in potential global climate change. However, carbon dioxide is also released when wood and other organic matter decays. Logging removes forest fuels from sites and can reduce the amount of carbon dioxide that would be released if the site burned. Fire suppression is not an effective way to mitigate this carbon dioxide release from many wildland fuels because in most cases, suppression only postpones burning. Decomposition by fire has occurred for millions of years in most of the vegetation types in western and northern North America. In the absence of fire, fuels tend to accumulate, ignition eventually occurs, and more carbon dioxide may be released than would have occurred under a natural fire regime. More fuel may be present, and fuel consumption may be more complete.

(2) Particulate matter. Particulate matter is the most important category of pollutants from wildland fire, because it reduces visibility and can absorb and transmit harmful gases. Particles vary in size and chemical composition, depending upon fireline intensity and the character of the fuels. Proportionately larger particles are produced by fires of higher fireline intensity (longer flames) than are found in low intensity and smoldering combustion fires (Ward and Hardy 1986 in USDA Forest Service and Johns Hopkins University 1989). Particulate matter emission factors for forest fuel types range from 4 to 180 pounds per ton (2 to 90 g/kg). For prescribed burning of logging slash, particulate production ranges from 18 to 50 pounds per ton (9 to 25 g/kg) for broadcast burning and 14 to 30 pounds per ton (7 to 15 g/kg) for piled slash. The amount of particulate released when burning sagebrush/grass fuel types averages 45 pounds per ton (22.5 g/kg), mixed chaparral ranges from 24 to 30 pounds per ton (12 to 15 g/kg), and emission factors for pinyon-juniper (slashed) range from 22 to 35 pounds per ton (11 to 17.5 g/kg) (Hardy 1990). The exact amount depends on the fuel type, the fuel arrangement, and the manner of combustion.

Emission factors for particulate matter less than 2.5 microns in diameter ($PM_{2.5}$) range from 9 to 32 pounds per ton (4.5 to 16 g/kg) for prescribed fires in the Pacific Northwest, averaging about 22 pounds per ton (11 g/kg). Emission factors are highest during the inefficient smoldering combustion stage and lowest during flaming combustion.

The amount of smoke produced depends on the total amount of fuel consumed. For example, even though the emission factor for sagebrush is higher than that for chaparral or pinyon-juniper, total smoke production from burning sagebrush is often lower because the total amount of fuel on a sagebrush site is generally less than on a chaparral or pinyon-juniper dominated site.

(3) Other emissions. Emission factors are available for other products of combustion such as the invisible gases. Emission factors for carbon monoxide range from 70 pounds per ton (35 g/kg) during flaming combustion to 800 pounds per ton (399 g/kg) for some smoldering fires.

Volatile organic compounds are a diverse class of substances containing hydrogen, carbon, and other elements such as oxygen. They include methane, polynuclear aromatic hydrocarbons (PAH's), and aldehydes and related substances. PAH's are not free in the environment as vapor, but are incorporated in fine particulates that are respirable. Methane and aldehydes are emitted as gases. Emissions for volatile organics vary from 4 to 50 pounds per ton (2 to 25 g/kg) of fuel burned, about half of which is commonly methane.

c. Emission rate. An emission rate is the amount of smoke produced per unit of time (pounds/minute or grams/second). The portion of the total amount of combustible fuel that a fire will consume for a given set of conditions is called available fuel, and is usually measured in tons per acre (kg/sq m) for forest fuels, and pounds per acre (kg/ha) for rangeland fuels. The land manager can make better estimates of emission rates from a prescribed burn if the amount of fuel consumed in each combustion phase is known. (See B.1.b.)

Fuel consumption rates are expressed as area burned per unit of time: acres per minute. Combustion rates can be calculated whether line-type ignition is used for backing or heading fires or area-type ignition is used in natural or activity fuels.

In order to estimate the emission rate, the following variables are required: available fuel (tons/acre), the combustion rate (acres/minute), and the emission factor (pounds/ton). The emission rate (pounds/minute) can be calculated by the following equation:

Emission Rate = Available Fuel x Combustion Rate x Emission Factor

The emission rate is used as an input to models that predict air pollutant concentrations. Such models can be used to assess the impact of smoke on visibility sensitive areas such as highways, cities, airports, and parks (Johansen et al. 1985).

3. Human Health Risk from Smoke. There is a growing awareness that smoke from wildland fires can expose individuals and populations to hazardous air pollutants. Concern is increasing over the risk to firefighters and the general public from exposure to toxins, irritants, and known carcinogens in smoke. A rigorous risk assessment is needed to address this increasingly sensitive issue. Although there is a low probability that public health is at risk, fireline workers are more likely to be harmed. Firefighters can be exposed to high levels of lung toxins such as aldehydes, acids, and particulates; to carcinogens such as polycyclic aromatic hydrocarbons, formaldehyde and benzene; and to carbon monoxide. These exposures may be at high levels for short periods, or at low levels for weeks at a time. The amount of some hazardous components of smoke, such as formaldehyde and respirable particulate matter, is well correlated to the amount of carbon monoxide (Reinhardt 1989). Relatively inexpensive devices for measurement of carbon monoxide (CO dosimeters) may provide a practical means to help recognize and prevent exposure of firefighters to dangerous levels of smoke.

The most likely effects of smoke on health are the aggravation of existing diseases or increased susceptibility to infection. Those most susceptible to exposure to air toxins include very young children and individuals with chronic lung disease or coronary heart disease. The effects of smoke on human health are discussed in detail in Sandberg and Dost (1990), Dost (1991), and the comprehensive study plan prepared by the USDA Forest Service and Johns Hopkins University (1989). The following discussion is summarized from these sources.

a. Criteria pollutants. The National Ambient Air Quality Standards are a set of goals established by the Environmental Protection Agency for acceptable levels of six air pollutants that are potentially harmful to public health. These criteria pollutants are particulate matter, carbon monoxide, sulfur dioxide, nitrogen dioxide, ozone, and lead.

(1) Particulate matter. The size class distribution of particles produced by forest fires is bimodal. Most of the particles have an average diameter of either 0.3 micrometers or greater than 10 micrometers (USDA Forest Service and Johns Hopkins University 1989). The proportion of particles in wood smoke less than 2.5 micrometers in diameter ranges from 50 to 90 percent (Sandberg and Dost 1990). Particles less than about 10 micrometers in diameter are able to traverse the upper airways (nose and mouth) and enter the lower airways starting with the trachea (Raabe 1984). As the particle size decreases below 10 micrometers, increasing proportions of particles are able to enter the trachea, and penetrate to the deeper parts of the airways prior to deposition. It should also be noted that once such particles reach the lower airways, it is likely that they will deposit on surfaces in the deepest parts of the lungs, the "pulmonary" zone--that part of the respiratory tract most sensitive to chemical injury (Morgan

1989 in Sandberg and Dost 1990).

National air quality standards assume that the components of particulate matter are essentially the same, regardless of location and source. However, the constituents of particulate matter vary widely. The particulate emitted by burning of vegetation has a much different composition and effect than that present in urban areas (Dost 1990). Particulate matter from vegetation fires consists mainly of condensed organic compounds. In urban areas, particulates contain compounds that rarely occur in rural vegetation smoke, such as masonry dust, fly ash, and asbestos. Also, other compounds present in urban air lead to a variety of chemical reaction products not likely to be found in association with wildland smoke. Smoke from wildland fuels is not as environmentally damaging as urban smoke.

(2) Carbon monoxide. Carbon monoxide is a product of combustion that is rapidly diluted at short distances from a fire and therefore poses little or no risk to community health (Sandberg and Dost 1990). However, carbon monoxide can be present at high enough levels near a fire to pose a hazard to firefighters, depending upon the concentration, duration, and level of activity of the firefighters at the time of exposure. Carbon monoxide is a chemical asphyxiant that interferes with oxygen transport in blood. Pilots exposed to carbon monoxide have developed headaches, fatigue, decreased concentration and impaired judgement. Data also suggest that long-term exposure to low levels of carbon monoxide produce accelerated arteriosclerosis, increasing the risk of cardiovascular diseases such as heart attack and stroke (USDA Forest Service and Johns Hopkins University 1989).

(3) Oxides of sulfur and nitrogen. Because forest fuels contain minute amounts of sulfur and somewhat higher levels of nitrogen, it is expected that these criteria pollutants are formed when wildland fuel is burned. Increased levels of oxides of sulfur have never been measured near wildland fires. Some oxides of nitrogen form, but the amount produced by forest burning is not significant enough to be of concern (Sandberg and Dost 1990).

(4) Lead. While a serious problem in urban pollution, lead is not a natural constituent of smoke from wildland fuels. It is assumed that lead may be only a minor component of wildland fire smoke when it has been deposited onto fuels from atmospheric sources, such as contaminated urban air that has moved into wildland areas (Ward and

Hardy 1986 in Sandberg and Dost 1990).

(5) Ozone. Much of the following discussion is summarized from Dost (1990). At lower altitudes, ozone is a common component of air, but at low enough levels to have an insignificant impact on human health. At high concentrations, ozone is a respiratory irritant, and can have a significant impact on individuals who already have serious respiratory impairment. The atmospheric chemistry of ozone formation is quite complex. It can form in the presence of atmospheric hydrocarbons generated in large quantities by the combustion of vegetation. The photochemical reactions that create ozone occur in areas of a smoke column that are penetrated by ultraviolet wavelengths of sunlight, particularly in the upper part of the plume. Ozone is therefore not likely to be a pollutant of concern to people in the immediate vicinity of a fire, although fire crews working at high elevations may find increased levels of this substance (USDA Forest Service and Johns Hopkins University 1989). Ozone may pose a problem in downwind areas affected by smoke, particularly in urban areas where ozone concentrations from other sources may already be high.

b. Non-criteria pollutants. Ambient standards have not been specifically identified by the Environmental Protection Agency for all components of smoke, although some of these substances can have negative effects on human health. The following discussion, taken largely from Dost (1990), describes the two groups of volatile organic compounds most likely to impact human health.

(1) Aldehydes. Aldehydes are classed as irritants, and some are potentially carcinogenic. The two aldehyde compounds found in smoke that are most likely to pose health problems are formaldehyde and acrolein.

(a) Formaldehyde. Formaldehyde is a very common atmospheric contaminant, found in association with building materials, textiles, preservatives, and medical activities. It has been measured as a by-product of burning wood, although little is known about its production in wildland fires. Formaldehyde is probably the most abundantly produced aldehyde, and is likely responsible for nose, throat and eye irritation in firefighters exposed to smoke. At higher concentrations, it may cause a reflexive decrease in breathing rates. Formaldehyde may not only thus contribute to mucosal irritation commonly experienced by firefighters, it also may interfere with their ability to obtain adequate oxygen at times when energy is most needed. Formaldehyde is rapidly transformed in the body to formic acid, a known toxin with a very slow removal rate. Formaldehyde also may be present in decreasing amounts in the smoke plume downwind, being slowly removed by chemical reactions.

(b) Acrolein. Acrolein is formed by few natural processes other than combustion. It has been measured in emissions from fireplace smoke, and studies suggest that greater amounts are produced in inefficient fires. Acrolein is a more potent irritant than formaldehyde. It has similar effects as formaldehyde to the respiratory system, but may also have severe toxic effects on cells. Individuals exposed to acrolein may have a decreased ability to repel respiratory infections. Acrolein is degraded by sunlight, and it is assumed that it slowly dilutes downwind with other components of smoke in the plume. If initial concentration levels are high, acrolein could be a significant irritant at a considerable distance from its source.

(2) Polynuclear aromatic hydrocarbons (PAH). Polynuclear aromatic hydrocarbons are a class of products that have been detected in wood smoke. These benzene containing compounds are incorporated as fine particles that are respirable. Some PAH compounds have carcinogenic properties. The likely risk to the general public of developing cancer because of exposure to these chemicals from prescribed fire is very small because of the rapid dilution of these products in the smoke plume (Sandberg and Dost 1990). However, very little is known about potential effects on firefighters from these compounds due to a lack of research on their production in wildland fires.

C. Resource Management Considerations

1. Control Strategies. When wildland fires occur, managers must consider the impacts on air quality and mitigate adverse effects whenever possible. Wildfire is evaluated through the Escaped Fire Situation Analysis, and prescribed fire through the Environmental Assessment and Prescribed Fire Planning process. There are strategic and tactical measures that can limit the amounts and mitigate the impacts of smoke from fires. The mitigation of adverse impacts can be accomplished through the selection and implementation of an appropriate control strategy. Managers can use these strategies to allow the burn to take place and yet reduce the risk of adverse effects of smoke. Clear resource management objectives and careful monitoring and evaluation of smoke impacts are keys to successful smoke control.

Managing smoke from wild or prescribed fires requires a daily prediction of smoke accumulations and whether they will reach unacceptable levels. Choice of suppression strategies and tactics must include a consideration of smoke effects on safety and visibility.

a. Avoidance. Avoidance is a strategy that considers meteorological conditions when scheduling burns to avoid incursions of smoke into sensitive areas. Burning should occur on days when weather conditions allow the transport of smoke away from populated areas. Smoke may not be such a limiting factor in sparsely populated areas, but any downwind effects should be considered when burning. The wind direction during both the active burning period (flaming stage) and the smoldering period must be considered. At night, downslope winds can carry smoke toward smoke sensitive areas, or allow valley bottoms to fill with smoke. Residual smoke emitted during the smoldering stage is especially critical.

b. Dilution. The dilution strategy controls the amount of emissions or schedules the rate of burning to limit the concentration of smoke in sensitive areas. The concentration of smoke can be reduced by diluting it through a greater volume of air, either by scheduling during good dispersion periods or burning at slower rates (burning narrow strips or smaller areas). However, burning at a slower rate may mean that burning continues into the late afternoon or evening when atmospheric conditions may become more stable. Burn when weather systems are unstable, but not at extremes of instability. The time of day at which ignition occurs is also important. Consider early morning ignitions to take advantage of weather conditions where improved mixing will occur as atmospheric heating takes place. Avoid days with low morning transport wind speed, less than 4 miles per hour (6.5 km/hr). Use firing methods to rapidly build a smoke column to vent smoke up to the transport wind and larger volumes of air. Using mass-ignition or rapid ignition will loft the column up and away from the unit, allowing for better dispersion and reduced emissions during the smoldering phase. Generally, a burn early in the day encounters improving ventilation; an evening burn encounters deteriorating ventilation.

c. Emission reduction. Emission reduction is an effective control strategy for decreasing the amount of regional haze and avoiding smoke intrusions into Designated Areas (DA's) (Sandberg et al. 1985). It reduces the smoke output per unit area, and is a concept applicable in both forest and rangeland areas. Most emission reduction techniques are based on limiting the consumption of larger fuels and soil organic layers. Large fuel consumption can be reduced by physically removing or scattering the larger fuels or burning when the larger fuels and duff are too wet to carry fire. Burning when the larger fuels or duff are wet will produce fewer emissions and allow rapid extinguishment of the fire. When windrowing and piling debris, allow fuels to dry before piling, and avoid mixing dirt into the pile. Emissions can also be reduced by use of a backing fire that results in more fuel consumption in the flaming stage, producing less smoke (Sandberg and Peterson 1987).

2. Techniques to Minimize Smoke Production and Impacts. Some smoke management techniques have application to both wildfire and prescribed fire situations, while others apply specifically to prescribed fire management.

a. All fire situations.

(1) Be sure that each burning operation has clear and concise management objectives that consider the impacts of smoke.

(2) Ensure that burn prescriptions and ignition plans provide for optimal smoke dispersion for the specific circumstances of the fire.

(3) Use the best weather data available to ensure adequate smoke dispersal. This includes obtaining spot weather and transport wind forecasts from the National Weather Service, taking weather at the burn site for several days prior to ignition, and validating the fire prescription and spot forecast with onsite weather observations. Wind speed and direction over the area can be checked by release of a helium balloon, or by observing the smoke from a test fire.

(4) Burn when conditions allow rapid dispersion. The atmosphere should be unstable so smoke will rise and dissipate, but not so unstable that control problems result.

(5) Burn when fuel moistures are higher and consume only those fuels that are specified in the treatment objectives. Higher duff moisture shortens the smoldering phase, thereby reducing residual smoke and particulate production.

(6) Mass ignition allows burning to occur with higher fuel moistures.

Higher temperatures generated by mass fire cause smoke to rise to a greater height above terrain than if a line ignition is used.

(7) Use a backing fire. The slow rate of spread and long residence time result in a higher fraction of fuel consumption in the flaming stage of combustion rather than in the smoldering stage. Since total smoke production per unit of fuel burned is considerably less during flaming combustion, backing fires favor lower total smoke production.

(8) The volume of smoke in a geographic area must be considered when making management decisions about prescribed burns, prescribed natural fires, or wildfires.

b. Prescribed fire.

(1) Burn other than in the "traditional" late summer and fall season. The impact on the air resource can be spread over a longer period, thereby reducing the possibility of a heavy smoke load on a particular day. Be careful of night burns because predicting smoke drift is more difficult, although night burning can be successful if properly planned and implemented.

(2) Burn fuel concentrations, piles, landings, and jackpots outside of the prescribed burning season. This increases the number of units that can be burned without overloading the airshed on days with good dispersal conditions.

(3) Public criticism of a burn program can be decreased by limiting its impact on recreational users. Avoid burning on days when smoke may affect Class I Areas and heavily visited recreational areas, or on holidays when many visitors may be using public lands.

(4) Using prescribed natural fire requires close monitoring of fuel loadings, fuel moistures, normal weather patterns, and down wind receptors in the area that may be affected by smoke drift.

(5) For prescribed natural fires, daily certification that the fire remains in prescription must include an assessment of smoke dispersal.

3. Participation in State and Local Smoke Management Programs. State and some local air quality agencies have mandatory smoke management programs. Programs are tailored to the needs of local and regional prescribed fire managers, while working to minimize adverse impacts of smoke.

a. Comply with air pollution and smoke management regulations. Know the regulations for your State and local area when developing the prescription. Details on State and local laws and regulations can be obtained from agency fire management or air quality staff.

b. Be pro-active in protecting air quality. Take part in the development (or update) of the State Implementation Plan that contains rules that govern prescribed burning. Working with State and local air quality agencies provides an opportunity for field input and some control over the future of prescribed fire.

D. Methods to Monitor Fire Effects

This section suggests methods for monitoring smoke effects that are practical for management purposes. Although there may be few State regulations that require monitoring of prescribed fire smoke, there are stewardship principles and ethical reasons that make monitoring a compelling aspect of a smoke management policy. As the first step, managers must develop and maintain an awareness of air quality monitoring techniques. Monitoring allows the evaluation of program adequacy and the effectiveness of communication with local air quality personnel. Implementation of air quality monitoring does not require having an elaborate array of monitoring instruments or hiring a monitoring contractor to evaluate fires.

While no readily available operational smoke monitoring techniques accurately predict the effect of a specific fire on air quality, understanding principles of air quality monitoring can result in better smoke management decisions. Some states are currently charging fees for burning, such as one fee to register each acre and an additional fee to burn the acre. This money is used to support the smoke management program and provide monitoring services for agencies doing prescribed burning. Local fire management officers should determine the proper level of monitoring and incorporate it into the burn plan. They should develop an objective method to monitor and evaluate the effectiveness of their smoke management efforts. Monitoring practices can range from simple to very complex programs as determined by managers or by the states. Agency specific guidance that identifies smoke management monitoring techniques and frequencies is provided in USDI-NPS (1992). The following are some practical procedures for monitoring and modelling smoke.

1. Visual Techniques.

a. Visual estimation. Visual estimation is the most common smoke monitoring method in use. Although most visual methods are subjective and limited, they are still very useful. When burning near smoke sensitive areas, a spotter on a hill away from the fire can watch where the smoke goes and relay information to the Burn Boss.

b. Aircraft tracking. Aircraft tracking of smoke plumes can be used to verify the source and trajectory of the smoke. It is used by some regulatory agencies to detect violations of air quality/smoke management regulations. This procedure provides a means to observe the loading of the airshed and to determine if additional burning should be limited.

2. Instrumentation.

a. Nephelometer. A nephelometer is an electronic device that measures the amount of particulate in a sample of air. This optical device measures the amount of light reflected from particles in the enclosed sample space. A nephelometer can be useful for safety monitoring, such as by measuring the amount of smoke on a highway. The machine could be programmed to flash lights as a warning when visibility is poor.

b. Filter sampler. Filter samplers draw a known volume of air through a filter. The filter is weighed before and after the sampling period, and the weight of particulate per volume of air can be calculated.

3. Computer Models.

a. SASEM. The Simple Approach Smoke Estimation Model (SASEM) is a screening model developed by the Bureau of Land Management and approved by the States of Wyoming and Arizona for estimating smoke impacts from prescribed fires. This model calculates emissions, and uses the emission figure to calculate down-wind concentrations of particulates. Estimated particulate loadings are compared quantitatively against ambient air quality standards to see if standards may be exceeded. (See Chapter XII.E.1., this Guide.)

b. TAPAS. The Topographic Air Pollution Analysis System (TAPAS) is a system of models for predicting the dispersion of air pollution over flat or mountainous terrain. Data on topography, wind speed, and direction are used to model plume direction and speed of smoke. Documentation and more information is available from the air quality staff, National Biological Survey, Environmental Science and Technology Center, Fort Collins, Colorado.

c. TSARS. The Tiered Smoke/Air Resources System (TSARS) is a group of computer programs that allows smoke management to be performed in a series of increasingly advanced levels of proficiency (Riebau et al. 1991). Tools with varying degrees of sophistication are available to model smoke production from wildland fires, producing results with different degrees of resolution. The level of analysis conducted can be matched to the complexity of the problem, or the expertise of the person using the model. Simple to use tools which produce easily interpreted results can be used at field levels, while more central offices in an agency would have access to more elaborate techniques. The components of the TSARS system were all derived from existing models, but have been modified for fires as the emission source and to have a consistent appearance to the user. See Chapter XII.E.2. for a more complete discussion of TSARS.

d. PUFF. PUFF is a plume trajectory model for multiple fires being developed for the Pacific Northwest. PUFF uses input on emission production, and models smoke dispersion for a specific grid of atmospheric temperature and pressure. Atmospheric conditions are derived from a National Weather Service model. These data can be input automatically from a computer that is operated by a private contractor. For more information, contact the U. S. Forest Service, Global Environmental Protection Project, Forestry Sciences Laboratory, Seattle, Washington.

E. Summary

The effects of smoke on health, air quality, and regional haze is very important to all land managers. They must recognize the need to manage smoke from wildland fires using the Best Available Control Measures. Every manager must determine the level of smoke management necessary to provide the least impact on the public, both in terms of health and visibility. The effects of smoke on firefighters also must be considered when managing wildland fires. If federal agencies do not take a rational, voluntary approach to smoke management, a mandatory approach may be provided that makes it more difficult to meet resource management goals and objectives.

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CHAPTER V - SOILS, WATER, AND WATERSHEDS

By Dr. Bob Clark

A. Introduction

Fire, either wild or prescribed, may have a wide range of effects on the soils, water, and watershed resources of forestlands, shrublands, grasslands, and wetlands. The wide range of effects is due to the inherent preburn variability in these resources, and to fire behavior characteristics, season of burning, and prefire and postfire environmental conditions such as timing, amount, and duration of rainfall. Further, effects of fire on some soils and watersheds are poorly documented and poorly understood. Thus, generalization about effects of fire on these resources is likely to be more risky and overstated than with any other managed resource.

This chapter, in keeping with the theme of this Guide, will discuss principles and processes that contribute to the effects of fire on soils, water, and watersheds. Where applicable, the opportunity to manage or influence these processes will be discussed. Also, methods for monitoring the effects of fire on these resources will be described, recognizing fire management investigation and monitoring needs for management purposes are not normally required to the degree and precision that are required at the research level. Finally, other factors are critical to "correct" prediction and evaluation of fire effects on soils and water; Chapter III.D. in this Guide is particularly relevant.

Excellent texts that provide basic information on soil taxonomy, properties, physics, and hydrology include those written by Soil Survey Staff (1975), Pritchett (1979), Hanks and Ashcroft (1980), and Branson et al. (1981). The ecology of the soil nitrogen cycle is well described in (Sprent 1987). Soil descriptions used in this chapter follow the nomenclature of the Soil Survey Staff (1975) unless otherwise noted. References to litter layers are described in Youngberg (1981). Important terms are identified in the Glossary.

B. Principles and Processes of Fire Effects

1. Soils. Most information about the effects of fire on soils is from forested land

and chaparral; also, much information is predicated on the effects of wildfire, not prescribed fire. By extrapolation, this situation has frequently led to the conclusion that fire is always detrimental to soils, including shrubland and grassland soils. However, in a history of fire research, Schiff (1962) indicated that researchers began documenting about five decades ago that in addition to negative effects, fire occasionally had beneficial effects on soil, and often had no measurable effect; further, the negative effects often were short-lived. These data are not meant to imply that the effects of fire are unimportant, because any negative effect, however small, can have substantial postfire consequences. The effects of fire on the soil resource are induced by soil heating, by removal of the protective cover of vegetation, litter and duff, or by the concentration of plant material substances in the soil. These effects are described in detail in Chandler et al. (1983), Wells et al. (1979), Wright and Bailey (1982), and other references listed in the Bibliography.

a. During the fire.

(1) Soil heating. The magnitude of the heat pulse into the soil depends on fuel loading, fuel moisture content, fuel distribution, rate of combustion, soil texture, soil moisture content, and other factors. The movement of heat into the soil is not only dependent upon the peak temperature reached, but even more so upon the length of time that the heat source is present. Because fuels are not evenly distributed around a site, a mosaic of soil heating occurs. The highest soil temperatures are associated with areas of greatest fuel consumption and the areas that have the longest duration of burning. In forested areas, high subsurface soil temperatures usually occur beneath fuel accumulations, with the highest temperatures most likely to be found in association with consumption of large piles of dry harvest residue or windthrow, or very thick duff layers. Because the pattern of soil heating varies significantly around a site, with differences in both the amount and duration of soil heating, a range of fire effects on soils can occur on one burned area.

Duff and soil moisture contents are critical regulators of subsurface heating. In a controlled soil heating experiment, the heat load into wet duff and mineral soil averaged 20 percent of the heat load that penetrated dry duff and mineral soil (Frandsen and Ryan 1986). Peak temperatures were more than 1000 F (538 C) greater where duff and soil were dry. DeBano (1977) estimated that about 8 percent of the heat generated in California chaparral fires is absorbed and transmitted downward into the soil. In general, "lightly burned" forests will cause maximum soil surface temperatures between 212 and 482 F (100 and 250 C) and the temperature 0.4 to 0.8 inches (1.0 and 2.0 centimeters) below the surface will not exceed 212 F (100 C) (Chandler et al. 1983). In "moderately burned" areas, surface temperatures are typically in the 572 to 752 F (300 to 400 C) range and may be between 392 and 572 F (200 and 300 C) at the 0.4 inch (1.0 centimeter) depth (Chandler et al. 1983). A "severely burned" area may result in surface temperatures approaching 1400 F (760 C) (Chandler et al. 1983).

In contrast, rangelands support considerably lighter fuel loadings and frequently result in fires of shorter duration that produce less subsurface heating. Rangeland fires typically result in soil surface temperatures from 212 to 730 F (100 to 388 C) although extremes to 1260 F (682 C) have been reported. The highest surface temperatures are probably associated with local accumulations of loosely arranged litter and intense winds created by the fire (Wright and Bailey 1982). The greatest subsurface heating likely occurs where thick, dry litter layers are consumed beneath shrubs and isolated trees. The soil heat pulse, including both amount and duration (DeBano 1979), is instrumental in eventual effects of fire on plants (see Chapter VI.B.1.c., and VI.B.2.c., this Guide) and in physical, chemical, and biological effects on soils.

Less is known about heat effects on wetland soils. Due to the high water content of wetland soils, penetration of heat generated by a surface fire can be significantly less than in mineral soils. Since many wetland soils are composed of significant amounts of organic materials, and organic matter has a lower thermal diffusivity than mineral soil, penetration of heat can be further reduced. However, organic soil layers can become dry enough to burn. Significant amounts of heat can be generated when organic soils burn, particularly in drought situations when the fire burns deeply into organic layers.

(2) Postfire temperature increases. Soil temperature may increase after a fire because of the removal of vegetative cover, consumption of fuels, thinning or removal of the litter and/or duff layer, and the enhanced "black body" thermal characteristics of charred material on the surface. This is of great significance in Alaska where permafrost (permanently frozen soil) is present. The soil layer above the permafrost thaws each summer, and is called the "active layer." Soil temperatures usually increase after a fire because fire removes the overstory vegetation, blackens the surface, and consumes some of the layer of moss, lichens, and semi-decomposed organic matter that insulated the soil from summer warmth. Soil temperatures were 9 to 11 F (5 to 6 C) greater at depths of 4 to 20 inches (10 to 51 centimeters) after fire in a black spruce/feathermoss stand in interior Alaska (Viereck and Foote 1979). Eight years after this fire, the depth of the active layer had increased from about 18 inches to 72 inches (46 to 183 centimeters) (Viereck and Schandelmeier 1980). The depth of the active layer eventually stabilizes, and then decreases to its original thickness. The length of time before this occurs depends upon the rate at which new vegetation grows and shades the soil surface, and how long it takes for a soil organic layer to develop that has the same insulating properties as the organic layer that was removed by the fire.

Under similar moisture regimes, warmer soils increase the rate of decomposition, and nutrient availability to postfire vegetation. Within physiological limits, higher soil temperatures also improve growing conditions for plants. In Alaska, deeper annual soil thawing increases the depth of soil available for rooting. This makes additional nutrients, especially nitrogen, available to plants, simply because they are not in frozen soils (Heilman 1966; 1968). Postfire vegetation productivity generally increases significantly after fire on permafrost sites (Viereck and Schandelmeier 1980), although the duration of this effect is undocumented.

b. Physical effects. Heating may cause changes in some physical properties of soils, including the loss or reduction of structure, reduction of porosity, and alteration of color. Most frequently, however, the important consequences include the reduction of organic matter, exhibition of increased hydrophobicity (nonwettability), and increased erosion due to the loss of protective plant and litter cover. Organic matter and hydrophobicity are discussed below under the heading "c. Direct chemical effects."

Erosion by wind (aeolian), water, or gravity often, but not always, increases following fire. The severity and duration of the accelerated erosion depend on several factors, including soil texture, slope, recovery time of protective cover, the amount of residual litter and duff, and postburn precipitation intensity. Raindrop splash, sheet and rill erosion, dry ravel, soil creep, and even mass wasting can occur. In extreme cases, such as steep, chaparral sites in the San Gabriel Mountains of southern California, erosion rates of more than 150 tons of debris per acre have been measured after wildfires (Krammes and Osborn 1969). It is reasonable to assume that hydrophobicity contributed to the extreme erosion rates reported from these areas (DeBano 1979). Extreme rates, up to 165 tons per acre, have also been reported following severe wildfires on timbered and chaparral sites with 40 to 80 percent slopes in Arizona (Wright and Bailey 1982). More commonly, erosion rates, even on steep slopes, range from about 23 to 52 tons per acre on granitic, sandstone, and shale-derived soils, and 7 to 10 tons per acre on limestone-derived soils (Wright and Bailey 1982). It is unclear from the literature how much of the soil movement is attributable to fire, because preburn soil movement or soil movement from unburned "control" areas is seldom reported.

Excessive erosion may not occur for several years after burning (Wright and Bailey 1982) because root systems of top-killed shrubs can maintain soil stability. Mass wasting apparently occurs when root systems begin to decay. If this occurs, it is reasonable to assume that rapid reestablishment of soil-stabilizing, deep-rooted shrubs (rather than shallow rooted grasses) is critical, especially on steep slopes. It has also been reported that coarse-textured soils are more erodible than fine-textured soils (Wright and Bailey 1982). This may explain why little soil movement occurs, even on steep slopes, following prescribed fires on sites with fine-textured Mollisol soils in Wyoming and elsewhere. In Alaska, however, fine textured permafrost soils tend to be much more erosive than coarse textured permafrost soils. Coarse textured soils usually have a low water content, while fine textured soils may contain as much as 50 percent ice. Postfire erosion on ice-rich permafrost soils occurs much more frequently where firelines have been constructed than on sites that have burned, because fires are seldom severe enough to completely remove the organic layer (Viereck and Schandelmeier 1980).

c. Direct chemical effects. Several chemical changes in soils may occur as a direct result of fire, including an increase in pH on some sites; the formation of water repellant soil layers, hydrophobicity, on some sites; and reduction in organic matter.

(1) Organic matter. The reduction of incorporated organic matter is critical if it occurs, on arid, semi-arid, and forested sites, because organic matter is a basic reservoir of the site nutrient (especially nitrogen) budget (Sprent 1987; Harvey et al. 1987). Organic matter helps regulate the hydrologic cycle and the carbon/nitrogen ratio, provides a site for nitrogen fixation by N-fixing bacteria, and maintains soil structure porosity and the cation exchange capacity. The amount of soil organic matter consumed by fire depends on soil moisture content, amount and duration of heating, and amount of organic matter available for combustion or distillation. For example, peat soils may burn extensively, whereas fire rarely affects most rangeland soils. Similarly, saturated soils rarely loose any organic matter whereas substantial losses may occur in dry soils.

(2) Hydrophobicity. The hydrophobicity phenomena is most common in the chaparral soils of southern California. Although not completely understood, the process by which hydrophobic soil layers form has been described in some detail by DeBano (1981). Organic compounds in litter, probably aliphatic hydrocarbons, are distilled during combustion, migrate into the soil profile, and condense on soil particles, forming a water repellant layer. The phenomena is most severe in dry, coarse textured (sandy) soils that are heated to 349 to 399 F (176 to 204 C). It is least severe in wet, fine textured soils where temperatures remain below 349 F (176 C). It also appears that high temperatures, above 550 F (288 C), destroy the compounds. These data suggest that fires that heat soils to an intermediate range of temperature are more likely to cause the formation of a non-wettable layer than fires that only heat the surface of the soil, or those that cause deep penetration of high temperatures; and that certain plant communities, such as those containing chaparral species, are more likely to be affected.

It is important to recognize that hydrophobicity occurs naturally, in the absence of fire, on forestlands, shrublands, grasslands, agricultural lands, and even golf greens around the world (DeBano 1969a, 1969b, 1981). In addition to the potentially severe problem in southern California, it has also been reported, although less severe and of shorter duration, in every western State except Alaska, New Mexico, and Wyoming (Branson et al. 1981, DeBano 1969a). There are several reported "benefits" of hydrophobicity, including evaporation control and water harvesting (DeBano 1981). One additional, unreported benefit occurred in central Oregon where precipitation limited reestablishment of lodgepole pine *(Pinus contorta)* following a severe wildfire. The presence of hydrophobic layers beneath large burned logs channeled water to inter-log areas, providing adequate soil moisture for seedling establishment.

(3) Acidity/alkalinity. pH is a standard measure of acidity or alkalinity, with 7.0 (i.e., the concentration of H^+ ions is 10 ^{7} equivalents per liter) being neutral on the pH scale of 1 to 14. The scale is logarithmic, so that water or soil with a pH of 5 is ten times more acidic than water or soil with a pH of 6. "Pure" water is neutral, although "pure" rainfall may have pH values between 5.4 and 5.6 due to absorption of CO_2 that reacts to form one or more weak acids. Understanding the pH concept allows understanding of the mechanisms by which fire alters soil pH and thus the soil nutrient regime.

The combustion process releases bound nutrients, many in elemental or radical form. Certain positive ions, collectively called cations, are stable at typical combustion temperatures and remain onsite after burning. They are subsequently washed into the soil where they exchange with H^+ ions; the resulting increase in H^+ ions in solution increases the pH. Nutrient availability is related to soil acidity (c.f., Tisdale and Nelson, 1975). Elements critical for plant growth, such as nitrogen and phosphorus, become more available to plants after a fire that raises the pH of an acidic soil. Fire can significantly enhance site fertility when it raises the pH on cold, wet, acidic sites.

Fire-induced increases in soil pH are widely reported (Chandler et al. 1983, Wright and Bailey 1982). Most cases of increased pH occurred on forest soils where the initial pH was acidic, and a large amount of organic material burned. Increases in

nutrient availability may be highly significant. Rarely do arid or semi-arid soils, which are typically alkaline, exhibit increased pH after burning. Those that do are near neutral initially, may increase a few tenths of a pH unit, then return to preburn pH levels within a year or two after burning. Little effect on the soil nutrient regime occurs.

d. Soil biota. Soil fauna are variously affected by fire (Ahlgren 1974, Chandler et al. 1983, Daubenmire 1968a, DeBano 1979, Mueggler 1976, Wright and Bailey 1982). Aboveground, soil-related herbivores and carnivores usually suffer drastic, but temporary declines, and may be eliminated by "clean" fires (Wright and Bailey 1982). Sub-surface animals respond differently, depending on both amount and degree of soil heating, the size of preburn populations, and the specific organism in question. One study of Douglas-fir *(Pseudotsuga menziesii)* residue reduction burning found that the bacteria *Streptomyces* were not affected by burning but mold populations were significantly reduced. In contrast, prescribed burning in jack pine *(Pinus banksiana)* resulted in greatly increased *Streptomyces* populations that were still increased into the third postburn growing season. Even where bacterial populations immediately decrease after burning, they typically increase dramatically following the first significant postburn rainfall (Chandler et al. 1983).

Fire induced changes in the soil environment may favor one soil microorganism to the detriment of another. Reaves (et al. 1990) reported that growth of populations of species of *Trichoderma*, a soil fungus, was encouraged in soils sampled from a ponderosa pine *(Pinus ponderosa)* site that had been burned by prescription. In a laboratory study, these fungi inhibited growth of *Armillaria ostoyae*, one of several species of *Armillaria* responsible for serious root diseases in coniferous forests and plantations.

(1) Soil moisture content. Fire-caused mortality of soil microorganisms can be related to the amount of moisture in the soil when a fire occurs. *Nitrosomonas* and

Nitrobacter, two bacteria groups critical to nitrification (Huber et al. 1977, Sprent 1987), are killed at 284 F (140 C) in "dry" soil but at 167 and 122 F (75 and 50 C), respectively, in "wet" soil (Chandler et al. 1983). This suggests that this sensitivity to heat may be critical to the recovery of low-nitrogen ecosystems.

Water in soil increases the rate of conductance so that elevated temperatures are reached more quickly in surface layers, especially in coarse soils. Therefore, the premise that soil temperature cannot exceed 212 F (100 C) until all moisture is evaporated is academic with respect to certain organisms that have lethal thresholds below the boiling temperature of water. It is important to note that susceptibility to the heat pulse is usually dependent on time-temperature interaction rather than peak temperature alone. If nitrogen fixing bacteria are a concern, the best treatment may be to burn when soils are wet or moist because they restrict the heat pulse to deeper soil layers.

(2) Mycorrhizae. Fire can have a significant, although indirect, effect on soil mycorrhizae. Mycorrhizal fungi form a symbiotic relationship with roots of most higher plant species of both forests and rangelands. The fungal strands absorb water and nutrients (particularly phosphorus) from the soil and translocate them to the roots of the host plant. The host plant provides photosynthetic products to the fungi. The presence of mycorrhizae can lengthen root life and protect them against pathogens (Harley and Smith 1983 in Perry et al. 1987), and can be critical for the establishment of some species of trees. Most mycorrhizal roots occur in surface soil horizons, particularly the organic soil layer, and decaying wood, especially large diameter decomposing logs. If fire removes most of the organic matter on a forested site, productivity may be significantly reduced for many years (Harvey et al. 1986). If fire kills all species of plants that sustain mycorrhizal associations, spores of these fungi may die after several years. It may then be difficult for desired species of plants to reestablish, either by natural regeneration, planting, or direct seeding.

An important mechanism for reintroduction of mycorrhizal fungi on burned forested areas is dispersal by chipmunks *(Tamias spp.)*. These animals eat fruiting bodies of mycorrhizal fungi in adjacent unburned areas, and spread spores in burned areas when they defecate (Maser 1978b and McIntyre 1980 in Bartels et al. 1985). Downed logs provide important travel lanes and home sites for chipmunks. Therefore, the presence of residual logs after a wildland fire enhances the reestablishment of mycorrhizal fungi, both by enhancing habitat for chipmunks, and providing suitable microsites for mycorrhizal infection and growth.

Little is known about the ecology of mycorrhizae in rangelands (Trappe 1981). Most plants of arid and semi-arid rangelands are mycorrhizal, and many of these same relationships may be true, particularly the association of mycorrhizae with organic matter.

e. Soil nutrients. Nutrient changes occur during combustion. Two distinctions germane to the discussion of nutrients include total site nutrient budgets vs. soilborne nutrients, and total nutrients vs. available nutrients. For example, sites with large volumes of woody material have considerable portions of site budgets bound in organic matter, in forms unavailable to plants. When this material burns, a large amount of nutrients may remain on the site in ash, may leave the site in fly ash or via overland flow, or may volatilize and leave the site in gaseous form. In any event, if bound nutrients leave the site, the site budget decreases but the soil reservoir may remain unchanged (Owensby and Wyrill 1973). Second, even though part of a nutrient's budget may be removed, the remaining portion may be converted into a different, more available form. This latter case is common with nitrogen, which volatilizes at low temperatures; when volatilization occurs, the site budget decreases, but usually the ammonium (NH_4^+) form increases. The ammonium form is directly usable by plants. It is also converted to nitrite by *Nitrosomonas*, then to nitrate, which is also directly usable by plants, by the *Nitrobacter* group. The net result is that while the total amount of nitrogen on a site decreases, the amount of available nitrogen frequently increases.

Postfire nitrogen accretion occurs by such means as fixation by heterotrophic bacteria and symbiotic fixation by nodulated plant roots. On forested sites, many "nitrogen fixers" such as alder *(Alnus spp.)* and ceanothus *(Ceanothus spp.)*, provide rapid recovery of nitrogen (Farnsworth et al. 1978, Raison 1979, Rodriguez-Barrueco and Bond 1968). Bacterial fixation in decomposing wood can also provide an important postfire nitrogen source. In contrast, on chronically nitrogen-deficient sites, including many semi-arid rangelands (Whitford 1986), nitrogen may be depleted by burning too frequently. Burning at intervals of less than 5 to 8 years depleted nitrogen on tobosagrass *(Hilaria mutica)* sites (Sharrow and Wright 1977).

Nitrogen is often the growth-limiting factor on many sites, and is therefore of major interest. Sulfur also volatilizes at low temperatures and its loss also may be important (Tiedemann 1987). Most of the remaining nutrients typically increase or remain unchanged after burning (Chandler et al. 1983, Mueggler 1976, Wright and Bailey 1982).

The cations released to the soil during combustion may be substantial where fire consumes heavy fuel loads on forest sites. However, this so-called "ash effect" is probably minimal on most rangelands. A rangeland site supporting 1,000 pounds (454 kilograms) of completely consumed vegetation per acre that contained 1 percent calcium, would only add about 10 pounds (4.5 kilograms) of calcium "fertilizer" per acre. Most vegetation contains about 3 to 6 percent cations.

2. Water. Wildland fire may affect both water quality and water quantity. The effects are summarized in Chandler et al. (1983), Tiedemann et al. (1979), Wright (1981), and Wright and Bailey (1982).

a. Water quantity. Plants, especially phreatophytes, transpire enormous quantities of water. It follows that breaking the soil-plant-atmosphere continuum should result in a net reduction in water loss. This concept has been applied, with mixed results, in attempts to increase water yield from watersheds (Branson et al. 1981, Davis 1984, Sturges 1983). For example, conversion of shrublands to grasslands has been thought to increase off-site water yield. More recently, Hibbert (1983) suggested that such practices in areas with annual precipitation less than about 15 to 20 inches (38 to 51 centimeters) will probably not result in increased off-site flow. It may be difficult to increase off-site water yield by any practical means in areas where evapotranspiration greatly exceeds precipitation.

There are no conclusive studies that clearly demonstrate that fire causes long-term increased water yield (Settergren 1969). Temporary (for a few years) increases may occur following large, "clean" fires because although direct evaporation may increase, water detention by litter and debris, and transpiration, both decrease. However, the effect is quickly reduced as vegetation and litter return. Demonstration of the "increased yield" is difficult because the effect is often temporally shorter than natural variation in climatic events, and because increased evaporation from the soil surface may compensate for reduced transpiration. There is good circumstantial evidence that greater accumulations of snow may occur following fires that remove some tree cover because of decreased interception of snow by the canopy. However, if the burned area exceeds about four times the height of surrounding cover, snow accumulation may decrease due to wind scour (Haupt 1979). In contrast, water quality may be dramatically affected by fire.

b. Water quality. The literature is replete with evidence of fire-induced changes in water quality, including increased sedimentation and turbidity, increased stream temperatures, and increased concentrations of nutrients resulting from surface runoff (Buckhouse and Gifford 1976, DeByle and Packer 1972, Feller and Kimmins 1984, Helvey et al. 1985, Nissley et al. 1980, Richter and Ralston 1982, Striffler and Mogren 1971, Tiedemann et al. 1979, Wright et al. 1976). The implication is clear: wild and prescribed fires, on forestlands, shrublands, and grasslands, have the potential to decrease on and off-site water quality, and should be mitigated. Effects may be short or long-lived. In a study on 26 to 28-inch (66 to 71 centimeters) annual precipitation rangeland with Mollisol and Inceptisol soils, Wright et al. (1976) found that level areas were unaffected, but adverse effects lasted for 9 to 15 months on moderate (8-20 percent) slopes and 15 to 30 months on steep (37 to 61 percent) slopes. Wright et al. (1976) further found that the average sediment yield was less than 0.01 tons per acre during the first six months after burning from the level sites but was about 10-fold greater on moderate slopes and 100-fold greater on steep slopes.

Mesic, forested sites revegetate much more quickly, but also may be exposed to greater, and often more intense, rainfall. In a study following a wildfire on a ponderosa pine site in central Washington, where annual precipitation is about 23 inches (58 centimeters), Helvey et al. (1985) found that annual sediment yields increased as much as 180-fold above prefire levels. The yields were still 12-fold greater after seven years. A carefully controlled study on a larch *(Larix occidentalis)*, Douglas-fir, and Engelmann spruce *(Picea engelmannii)* site in western Montana (DeByle and Packer 1972) found that sediment returned to preburn levels after about four years. Erosion rates in the Montana study remained below 0.01 tons per acre per year throughout the study.

Methods for mitigating accelerated sedimentation due to fire have not been fully developed. Sedimentation may be reduced by the protection of steep slopes, retention of wide buffers along water courses, rapid revegetation, the presence of residual fuel and duff, and the exclusion of use until recovery.

Fire may induce sudden changes in water chemistry. Such changes probably result from nutrients that are carried into water courses from burned areas. Typically, several forms of nitrogen, phosphorus, and most cations show increases in stream water after burning (Tiedemann et al. 1979). Chemistry is most often altered during the first few storms following fire. Changes include increases in bicarbonates, nitrates, ammonium, and organic nitrogen (Chandler et al. 1983). These nutrients usually are not hazardous to humans but may contribute to eutrophication or algal blooms. Water quality typically returns to preburn levels within one to two years. Some fire retardant chemicals used during fire suppression may be toxic to aquatic animals; the addition of these chemicals near or in water courses should be avoided until specific consequences are clarified.

Stream temperatures also often increase after fire occurs. Usually the temperature increase is due to the removal of overhead protective vegetation rather than direct heat flux from the fire. Elevated stream temperatures are detrimental to most cold water fish species. Therefore, protection of streamside vegetation, and quick revegetation of burned areas, are critical to stream rehabilitation.

C. Resource Management Considerations

1. Expertise on Interdisciplinary (I. D.) Teams. Expertise in soils and hydrology is required on interdisciplinary teams.

a. A soil scientist, knowledgeable about fire effects, should be assigned to interdisciplinary teams involved with fire prescription development, site selection, emergency fire rehabilitation projects, and wildland fire suppression activities.

b. A hydrologist should be assigned to the I.D. team, or at least consulted, if wild or prescribed fire might affect water quality, on or off-site.

2. Statistical Analysis. Statistical analysis is necessary to assess the effects of fire on soils and hydrology.

a. Physical and chemical characteristics of soils typically are extremely variable. Fire effects can vary significantly around a site because of differences in the amount of soil heating. A biometrist or statistician should be consulted before any sampling is undertaken.

b. Adjacent, unburned "control" sites should be used for comparison with burned sites whenever possible to evaluate the effects of fire on soils or water. A biometrist or statistician should be consulted for appropriate sampling and comparison methods. **3. Limited Ability to Extrapolate to Other Sites.** Much of the fire literature describes the effects on soils and hydrology of intense wildfires. Such information should be extrapolated to different regions, soils, environmental conditions, types of fire behavior and characteristics, and to prescribed fires with caution.

4. Variability of Effects. Because fire effects on soils and water are highly variable, consideration should be given to locally documenting effects and relating the effects to fireline intensity, burn severity, fuel, duff, and soil moisture content at the time of the fire, and other appropriate factors.

5. Factors Related to Postfire Erosion. Potential for wind, water, or gravity (especially dry ravel) erosion should be given strong consideration in the timing (i.e., fall vs. spring) of prescribed fires, and in the methods, timing, and species proposed for emergency fire rehabilitation.

a. Delayed recovery of vegetation and slope steepness appear to be important factors in accelerated erosion.

b. The presence of large woody debris and duff after a fire helps to protect the soil from erosion.

6. Management of Soil Heating. The amount of soil heating caused by prescribed fires in forest or woodland areas can be managed.

a. The distribution of soil heating is affected by the choice to broadcast burn, pile burn, or burn windrows. Also, the piling method may be important because machine piles tend to be "dirtier," and hold heat longer, than hand piles.

b. Small diameter, unmerchantable trees (whips) can be slashed just before fire, when they are still green and will not burn well, and thus can contribute little to soil heating.

c. Higher levels of utilization or yarding some unmerchantable material in areas with heavy dead and down fuel loads can decrease the amount of potential soil heating.

d. Burning an area while moisture content of large diameter fuels, lower duff, and soil is high will limit the duration of the fire and the amount of heat penetration into lower soil layers.

e. Rapid ignition techniques (e.g., aerial drip torch) can sometimes be used to shorten the duration of the burn, and thus the amount of soil heating.

7. Leaving Woody Material. When prescribed burning, it is important to leave some coarse, woody debris on the site for nutrient cycling and mycorrhizal function. Agencies may have specific requirements for retention of downed, woody material.

8. Riparian Areas.

a. Buffer strips. When prescribed burning, leave unburned strips of vegetation along riparian areas to serve as slope stability buffers, and decrease the potential for stream sedimentation. Width of buffer strips should be in accordance with applicable agency policy.

b. Season of fire. Riparian areas should be burned, if necessary, in spring when conditions are favorable for rapid recovery of adjacent vegetation.

c. Use of fire retardant. Use of fire retardant chemicals in or near waterways should be avoided. Fire retardant has the greatest impact on small or slow moving bodies of water.

d. Firelines. On erosive soils and/or steep slopes, restrict the location of firelines that lead directly into water courses. Rehabilitate any firelines that were constructed as soon as possible. Replacement of soil and plant material removed during construction is an effective method of fireline rehabilitation.

9. Salvage Logging. Know the potential for soil erosion when considering or planning salvage logging operations after wildfire.

a. Road construction may increase the amount of soil erosion and mass movement. Also, some areas (e.g., Western Oregon) have restrictions to limit "off road" use to minimize compaction. These restrictions may dictate the appropriate logging method.

b. A choice may be made to helicopter log or to not log at all.

10. Need for Closures. It may be necessary to close burned areas to all types of vehicular use, and other uses, for several years because of increased erosion potential.

D. Methods to Monitor Fire Effects

The effects of fire on soils and water are usually extremely variable over time and space due to variations in soil characteristics and plant communities; in the intensity, duration, and timing of postfire precipitation; and in the heat regime of the fire. Many methods used to monitor changes in soils or water quality are time consuming, expensive, and often require elaborate laboratory facilities. Therefore, methods used to monitor fire effects for day-to-day management purposes are usually less extensive and intensive than methods used for research. This section suggests methods for monitoring fire effects that are practical for management purposes. A more complete understanding of soil monitoring techniques can be gained from Black (1965) and Golterman and Clymo (1969).

1. Soil Temperature. Soil temperature, by itself, may not be particularly revealing. However, it may add valuable insight when used in conjunction with other information.

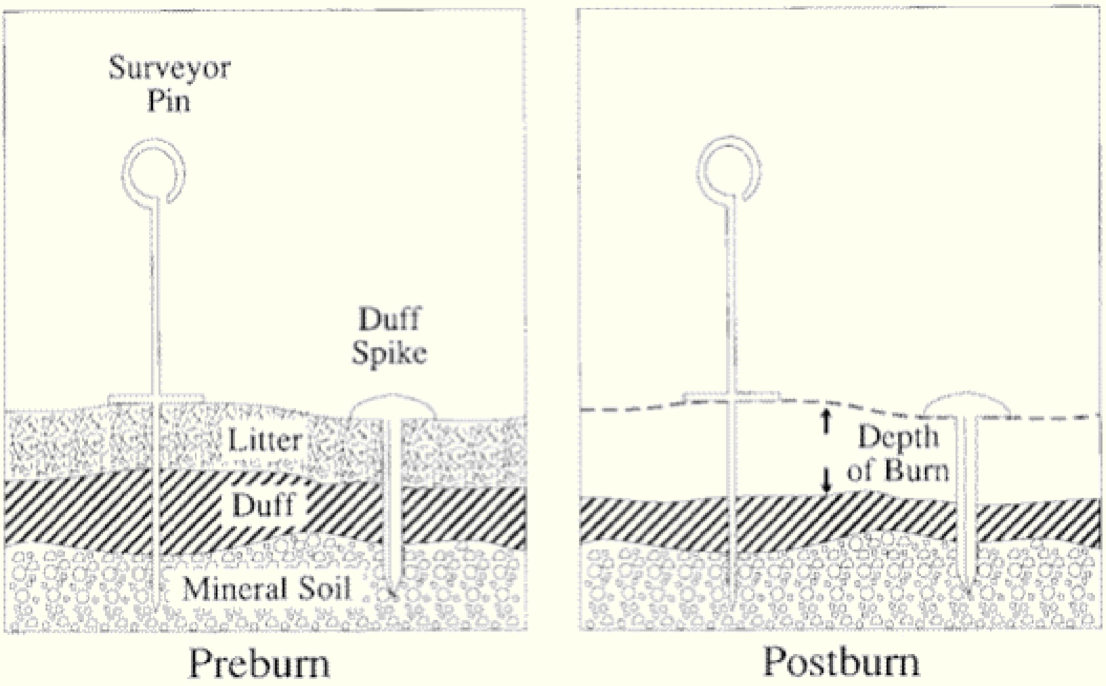
a. Heat sensitive paint. Temperatures can be monitored by placing chips covered with heat sensitive paints at the duff/soil surface and at various depths below the surface. These paints turn color at a temperature specific to each kind of paint, but do not indicate duration of heat. However, it is likely that the presence of high temperatures may increase the certainty of impacts. Temperature sensitive devices and paints are available from many forestry suppliers.

b. Electronic equipment. Extremely accurate data can be obtained through use of sophisticated electronic equipment such as thermistors and thermocouples. A thermocouple can be wired to a strip chart recorder which provides a continuous record of temperature. These are expensive, and can be unreliable unless properly used. Unless research is being conducted on a prescribed fire, their use is probably not warranted. If they are used, advice should be obtained from the research community on appropriate composition, size, number, and placement of thermocouples.

2. Soil Physical Properties. The primary physical effect of fire on soil is the removal of protective cover, which allows accelerated erosion. Erosion can be estimated using predictive models, qualitative guides, or quantitative methods. To isolate fire effects from other effects, burned areas should be compared with adjacent, unburned control areas. The following practical, quantitative methods are suggested for obtaining direct estimates.

a. Erosion.

(1) An appropriate number of "depth-of-burn" pins can be randomly placed onsite before burning to measure duff removal and/or subsequent soil movement. The pins may be of the v-notched survey pin type (with the pin inserted such that the notch is at duff or soil surface level), or the t-bar survey pin type (with the pin inserted such that the cross member rests on the duff or soil surface) (McRae et al. 1979). Bridge spikes also work well. Remeasurements over time will provide an indication of soil movement. Frost heaving and pin disruption by animals may produce erroneous values. Depth of soil removed can be expressed as volume or mass by using appropriate mathematical conversions. This method of estimating soil movement appears to work well for relatively uniform erosion of minor depth, such as wind erosion, but does not work well for irregular soil movement, such as gully erosion, or for mass wasting.



(2) Soil erosion bridges (Blaney and Warrington 1983, Ranger and Frank 1978) are excellent devices for estimating the amount of soil leaving the site, but may require special or additional equipment. Staff soil scientists, or soil scientists from the USDA Soil Conservation Service, universities, or experiment stations should be consulted.

(3) Soil catchments or erosion troughs (Ryan 1982, Wright et al. 1976) are used to collect material after it leaves the site. Commonly, paired watersheds (one member of the pair receives the treatment and the other serves as an untreated control) are used to estimate off-site movement of soil. This method requires the construction of catchments and may not be practical on wildfires or on most prescribed fires.

(4) Other methods are available for estimating accelerated erosion, including models such as the Revised Universal Soil Loss Equation (Renard et al. 1991), radioactive markers (Lance et al. 1986), and photogrammetry (Lyon et al. 1986). These methods are especially useful for research and special management needs, but may not be practical in most fire situations.

b. Hydrophobicity. Hydrophobicity is most easily estimated by the water drop penetration time method (DeBano 1981). A water drop is placed on the sample surface and the length of time to be absorbed is monitored. DeBano suggests that water droplets remaining longer than 5 seconds indicate water repellency. A further refinement of this method uses the surface tension of various ethanol solutions; a water repellency index is then obtained by dividing the critical surface tension into the time (up to 600 seconds) required for water drop absorption. An index value greater than 10 indicates extreme repellency, 1 to 10 indicates moderate repellency, 0.1 to 1 indicates slight repellency, and less than 0.1 indicates wettability.

c. Other physical properties. Fire-induced changes in other physical properties of soils, including soil structure, porosity, and rate of infiltration can be measured using standard methods (Black 1965) for soil analysis. A soil scientist familiar with the methods should perform these analyses.

3. Soil Chemical Properties.

a. Soil water content. Soil moisture content partially regulates the heat pulse into the soil. Because of this importance it is discussed separately here. Several methods of soil water determination are readily available (Roundy et al. 1983) but the gravimetric method (Gardner 1965) is probably the most reliable and commonly used method. An appropriate number of 1 to 100 gram samples are collected in soil cans, weighed (wet weight), oven dried to constant weight (normally at 212 F [100 C]), and reweighed (dry weight). Soil water content is then calculated according to:

soil water content (percent) = (wet weight - dry weight x 100) / dry weight

Drying at temperatures greater than 212 F (100 C) can cause volatilization of soil organic matter, resulting in a loss of materials other than water from the sample, and an overestimation of soil moisture content.

b. Soil pH. The acidity of soil is readily determined using soil paste or aqueous soil suspension and glass electrode pH meters (Peech 1965). Although "standards" are used for meter calibration, it is important to concurrently analyze soil samples from adjacent, untreated soils for comparison, because variations occur among meters and investigators.

c. Soil conductivity. The electrical conductivity of soil caused by the presence of soluble salts is readily determined by using a solu-bridge (Bower and Wilcox 1965). Extracted soil solution is read on the bridge, corrected for temperature, and reported in millimho (unit of conductance). High soil salt content is an indicator that salt-tolerant species should be planted.

d. Other chemical properties. Measurement of other chemical properties of soils that are likely to be affected by the fire require special laboratory equipment and procedures. These are probably beyond practicality for routine fire effects analyses. Bureau soil scientists or soil scientists of other agencies, universities, or experiment stations should be contacted if such analyses are necessary.

4. Water Quantity. Increases in off-site water yield due to burning are most easily determined by measuring changes in streamflow volume before and after burning. If available, paired watersheds should be used. Other agencies, such as the USDA Soil Conservation Service or DOD Army Corps of Engineers, often have gaging stations or use other methods to determine flow volumes on many streams and rivers. In addition, these agencies and many universities and experiment stations often have portable devices that can be used to assess changes in water yield.

5. Water Quality. Several descriptors of water quality can be estimated with minimal investment of time, equipment, training, and personnel, and include turbidity, conductivity, dissolved oxygen content, and temperature. Kits and relatively inexpensive instruments are commercially available for sampling these properties. Experiment stations, universities, and Federal and State water quality agencies can provide assistance.

a. Sedimentation and turbidity. Sedimentation and turbidity reduce the quality of spawning areas and reduce photosynthetic activity. These effects can be amplified by fires that occur near water and may persist for several years or longer. Platts et al. (1983) described general methods for sampling and evaluating stream conditions. Specific procedures for the nephelometric turbidity estimation method are contained in the EPA (1979) publication on water quality evaluation methods.

b. Conductivity. Changes in the specific conductance due to increased ionic composition of the water may provide a useful estimate of the addition of nutrients or contaminants to water. Specific procedures for the use of conductivity meters are found in EPA (1979).

c. Dissolved oxygen. A dissolved oxygen content of about 5 milligrams or more per liter may be necessary to maintain aerobic conditions and support cold water fisheries in Western streams (EPA 1976, Thurston et al. 1979). Because the addition of sediment and nutrients following fire may reduce the oxygen content below acceptable levels, oxygen contents can be monitored to estimate potential impacts on fisheries. Inexpensive kits and meters for measuring dissolved oxygen contents are readily available from chemical and forestry equipment suppliers. The EPA (1979) described specific procedures for using the membrane electrode and modified Winkler methods of dissolved oxygen analysis. A hydrologist, fisheries biologist, or chemist should be contacted for recommendations of preferred methods and equipment in specific locations.

d. Temperature. Reasonably correct estimates of temperature may be important because water temperature, outside of some fairly narrow ranges, can dramatically influence algal blooms, fish survival and reproduction, and a host of other biological activities. However, precise estimates of temperatures in streams can be difficult to obtain because such factors as diurnal variation, angle of the sun, shading, and flow can contribute to error. These factors, as well as thermal layering, can cause equally bad estimates in lakes and ponds. Therefore, depending on the significance of temperature in a particular situation, a temperature sampling scheme should be carefully designed. It should also be noted that data obtained from monitoring and recording devices are usually more reliable than "grab samples" obtained with hand-held mercurial thermometers. Specific procedures for estimating the temperature of water are found in EPA (1979).

e. Other chemical properties. Measurement of other chemical properties of water, such as the concentrations of specific chemicals or nutrients, are probably beyond the practical reach of most land management agencies. Such analyses require special and expensive laboratory equipment and training. If such analyses are necessary, a hydrologist, fisheries biologist, or chemist should be contacted, and appropriate procedures (EPA 1979, Golterman and Clymo 1969, Hem 1970) applied. Analyses can sometimes be completed using inexpensive soil or water testing kits. Results from such testing are not definitive and should remain suspect until confirmed by standard laboratory procedures.

E. Summary

The effects of fire on soils, water, and watersheds are extremely variable. In some cases, such as accelerated erosion, the outcome is reasonably predictable and mitigating measures such as rapid revegetation are necessary. In other cases, such as change in off-site water yield after burning, the outcome is much less predictable because it appears to depend on site-specific characteristics and on unpredictable climatic events. The application of mitigating measures must be based on local experience and local research. In almost all cases, the establishment of a local data base would provide useful information for future events.

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CHAPTER VI - PLANTS

By Melanie Miller and Jean Findley

A. Introduction

This chapter discusses the interaction of fire with plants. It explains the basic principles and processes that determine how plants are affected by fire, and the factors that control plant response after the fire. Documentation of burning conditions and fire characteristics provides important information for understanding postfire vegetative response. Use of appropriate techniques when monitoring specific effects of fire on vegetation is necessary to detect changes that occur in the postfire plant community. The goal is to enable managers to predict fire effects on plants based upon knowledge of burning conditions and prefire species and community characteristics, and to interpret the causes for observed variability in postfire vegetative response.

The response of plants to fire can vary significantly among fires and on different areas of the same fire. Both variability in the heat regime of the fire and differences in plant species' abilities to respond affect the postfire outcome. Fireline intensity, burn severity, total duration of combustion, soil heating, time of the year, and time since the last fire all influence mortality or survival of the plants, and thus subsequent recovery. Postfire effects also depend upon the characteristics of the plant species on the site, their ability to resist the heat of a fire, and the mechanisms by which they recover after fire. Plant recovery can be affected by factors that vary with growing season, or age of the plant. Whether the plants that first appear after a fire successfully establish on the site can be influenced by external factors such as postfire weather, postfire animal use, and plant competition.

The inherent abilities of plants to respond to fire depend partially on the fire regime to which the plant community has adapted. For example, a community may characteristically have been subject to frequent, low intensity, low severity understory fires, or the site may have experienced infrequent high intensity fires that killed all standing vegetation. Knowing the "natural" role of fire on a site gives an indication of the type of plant adaptations to fire that may be present.

The most significant sources of heat from most fires are downed dead surface fuels, litter, and duff layers. However, dead branches, leaves, or needles within a plant itself can produce a considerable amount of heat. Old decadent stands of shrubs may produce a more intense fire than a young shrub stand, which may have little dead or dry material and cannot be ignited. The amount of dead woody fuel, thickness of litter and duff layers, and amount of dead material within or around a living plant may be greater than "natural" if fire has been excluded from an environment in which fires used to occur at a moderate to high frequency. In this situation, the impact of fire on the vegetation may be different than it would have been under natural conditions because of the potentially higher temperatures and longer duration of fire that can occur.

B. Principles and Processes of Fire Effects

1. Plant Mortality. Fire-related plant tissue mortality is dependent upon both the temperature reached and the duration of time it is exposed to that temperature. The lowest temperature at which plant cells die is between about 50 to 55 C (122 to 131 F) (Baker 1929 in Wright and Bailey 1982). Some plant tissue may be able to withstand an exposure to 60 C (140 F) for a few seconds, but dies if exposed for about 1 minute. Plant tissue can sustain higher temperatures for greatly decreasing periods of time. Douglas-fir *(Pseudotsuga menziesii)* needles can tolerate temperatures of 70 C (158 F) for only about 0.01 second (Silen 1960 in Martin 1963). Additionally, some plant tissues, particularly growing points (meristems or buds) tend to be much more sensitive to fire heat when they are actively growing and their tissue moisture is high, than when tissue moisture content is low (Wright and Bailey 1982). Thus, plant tissues more readily die after exposure to a specific temperature for a certain length of time when actively growing than when they are physiologically dormant or quiescent, or have finished active growth for the year. Susceptible plant tissue may not be directly exposed to fire heat, because it is protected by other tissues such as bark or bud scales, or is buried in duff or soil. Plant mortality depends on percentage of tissue killed, location of dead tissue, reproductive mechanisms, and species ability to recover from injury.

a. Crown mortality. Both structural and physical characteristics affect the likelihood that the aboveground part of a woody plant will be killed by a given fire. Important crown characteristics include branch density, ratio of live to dead crown material, location of the base of the crown with respect to surface fuels, and total crown size (Brown and Davis 1973). Small size buds are more likely to be lethally heated because of their small mass. Large buds, such as on some of the pines, are more heat resistant. For conifers, long needles provide more initial protection to buds than short needles that leave the bud directly exposed to fire heat (Wagener 1961 in Ryan 1982).

The moisture content of new needles, leaves, and small twigs, the foliar moisture content, fluctuates throughout the growing season. It is highest during the period of active leaf formation and shoot elongation (greenup), subsequently declines to a lower level during the remainder of the growing season, and drops again when foliage cures (Norum and Miller 1984). For conifers, the moisture content of new foliage follows the above pattern, while moisture levels in older needles drop in the spring, and rise again in late spring and early summer (Gary 1971; Chrosciewicz 1986). Moisture content influences foliar flammability because leaves and twigs containing more water require a greater amount of heat to raise them to ignition temperature. Coniferous tree crowns seem to be more susceptible to crown damage in the spring than they are in the fall because tissue moisture of new growth is highest at about the same time the moisture content of old foliage is near its seasonal low and more flammable. The foliage of some shrubs, particularly those with evergreen leaves, contains flammable compounds that allow foliage to burn more readily than if these compounds were not present (Countryman and Philpot 1970; Shafizadeh et al. 1977).

The scorching of a tree crown is primarily caused by peak temperatures associated with the passage of the flaming fire front (Wade 1986). The height above the surface to which crowns are scorched, (crown scorch height), can be estimated from flame length, an output of the Fire Behavior Prediction System, ambient air temperature and windspeed (Albini 1976). (See XII.D.1.a., this Guide, for a more complete discussion of how this model works.) Long-term heating caused by burnout of fuel concentrations after the flaming front has passed can also scorch crowns. The percent of crown volume with scorched foliage is a better indicator of fire impact than crown scorch height because it considers the proportion of live foliage remaining (Peterson 1985). For conifers with short needles, and trees and shrubs with small buds, crown scorch is often equivalent to crown death because of lack of protection afforded the buds (Wade 1986), and the low heat resistance of small buds and twigs.

Crown consumption is the result of the ignition of needles, leaves, and twigs. Needle ignition occurs at about 400F (220C) (Wade and Johansen 1986). For fire resistant conifers with long needles, such as ponderosa pine *(Pinus ponderosa)*, and/or large or well protected buds that are buried in wood such as western larch *(Larix occidentalis)*, crown consumption is often a better indicator of crown mortality than crown scorch. For these species, bud and twig death generally only occurs where foliage is consumed by fire (ibid.).

b. Stem mortality. Trees and shrubs can be killed by lethally heating the cambium, the active growth layer that lies beneath the bark. Bark surface texture can affect its likelihood of ignition, whether stringy and flammable, or smooth. Fire resistance of tree stems is most closely related to bark thickness, which varies by species and with age. The cambium layer of thin barked trees such as lodgepole pine *(Pinus contorta)*, subalpine fir *(Abies lasiocarpa)*, aspen *(Populus tremuloides)*, madrone *(Arbutus menziesii)*, or most of the spruces *(Picea spp.)* is usually dead beneath any charred bark. Heat released in the flaming front, and hence flame length, can be a good indicator of the amount of injury sustained, and even the mortality of thin barked species. External char is not a good indicator of cambium damage on thick barked trees such as ponderosa and Jeffrey pine *(Pinus jeffreyi)*, Douglas-fir, or western larch (Ryan 1982). The cambium beneath thick bark layers is usually only killed by heat released over a long duration, such as from burnout of logs, and deep litter and duff layers, which cannot be predicted by the Fire Behavior Prediction System. The amount of bole damage was a better indicator of postfire survival of Douglas-fir after a series of spring and fall underburns than either scorch height or the percentage of crown volume scorched (Ryan et al. 1988). Once tree cambium is wounded by fire or mechanical damage, it is often more susceptible to additional injury by fire, both because the bark is thinner near the scar, and because of pitch that is often found in association with wounds. A model that estimates tree mortality based on species, and the amount of crown and bole damage is described in XII.D.1.b., this Guide.

Bark thickness, texture, and the presence of wounds or pitch also can affect the likelihood of mortality of shrub stems. However, because of the relatively small diameter of most shrub stems, most stems are girdled by any fire that reaches into their canopy, unless heat is present for only a very short period of time.

c. Root mortality. As with tree and shrub crowns and stems, there are physical and structural characteristics that affect root damage. Structural support roots growing laterally near the surface are more susceptible to fire damage and consumption than those growing downward. Roots found in organic layers are more likely to be lethally heated or consumed than those located in mineral soil layers. This makes shallow-rooted trees more subject to postfire windthrow. Most plants have feeder roots. Tree feeder roots collect most of its water and nutrients, are very small in diameter and are usually distributed near the surface. If most of the feeder roots are located in soil organic layers rather than in mineral soil, they are much more subject to lethal heating and consumption. While this may not always kill the tree, it can place the tree under significant stress. If fire has been excluded for a long time from areas that formerly had a high fire frequency, increased amounts of root (and bole) damage may result from fires smoldering in accumulations of litter beneath trees (Herman 1954 and Wagener 1955 in Wade and Johansen 1986).

Damage to roots and other subsurface plant parts cannot be predicted by the general behavior of the surface fire, nor by any specific descriptors of surface fire activity, such as fireline intensity, flame length, or rate of spread. Temperatures reached in the flaming front may be extremely high, but most of that heat is directed upwards. The mortality of buried plant parts is much more dependent on the total residence time of the fire, the length of time a heat source is present (Wade 1986), not just the length of time flaming combustion occurs. The subsurface heat regime of a fire is influenced by the amount of surface dead fuel, the amount and compactness of litter and duff, and the moisture content of those materials.

Burn severity (see II.B.6.e.), a qualitative measure of the amount of consumption of surface fuels and duff layers, is an indicator of subsurface heating. Soil moisture also retards penetration of heat into soil layers (Shearer 1975; Frandsen and Ryan 1986), thus protecting subsurface plant structures. There is some relationship between heat per unit area, the total amount of heat released in flaming combustion, and root damage, particularly if only a thin layer of combustible fuel is present. However, if moderate to heavy accumulations of surface dead fuel or organic layers exist, their consumption in smoldering and glowing combustion is the best indicator of significant amounts of subsurface heating. (Factors that regulate fuel and duff consumption, and thus burn severity, are discussed more completely in III.B.2. and III.B.3., this Guide.) There may be considerable damage or consumption of roots when little or no damage is apparent in tree or shrub crowns (Geiszler et al. 1984 in Wade and Johansen 1986). The amount of subsurface plant mortality can be indirectly estimated by knowing the location of roots and other buried reproductive structures, and relating this to classes of burn severity.

Plant mortality is often the result of injury to several different parts of the plant, such as crown damage coupled with a high percentage of cambial mortality. Mortality may not occur for several years. Death is often the result of secondary infection by disease, fungus, or insects, because the resistance of plants to these agents is often lowered by injury, and wound sites provide an entry point for pathogens (Littke and Gara 1986). A plant weakened by drought, either before a fire or after wounding, is also more likely to die.

2. Vegetative Regeneration. Sprouting is a means by which many plants recover after fire. Sprouts can originate from plant parts above the ground surface or from various levels within the litter, duff, and soil layers. Where sprouts originate and the depth below the surface at which buried plant parts are found can be species specific characteristics (Flinn and Wein 1977). Heat released in the flaming front of the fire can have a direct impact on mortality of sprouting sites that are above the ground surface. The same factors that control mortality of roots affect mortality of buried reproductive structures of woody plants, grasses, and forbs.

a. Location of dormant buds. Dormant buds are often located on laterally growing stems. Stolons are stems that run at or near the surface of the ground, producing plants with roots at intervals, such as a series of strawberry plants. Rhizomes are laterally growing underground stems located at varying depths in litter, organic, and mineral soil layers. They have a regular network of dormant buds that can produce new shoots and roots. Rhizomes are a structure common to many plants, including blue huckleberry *(Vaccinium globulare)*, thimbleberry *(Rubus parviflorus)*, Oregon grape *(Mahonia spp.)*, common snowberry *(Symphoricarpos albus)*, shiny-leaf spiraea *(Spiraea betulifolia)*, heartleaf arnica *(Arnica cordifolia)*, gambel oak *(Quercus gambelii)*, bittercherry *(Prunus emarginata)* and chokecherry *(Prunus virginiana)*.

Many plants have buds located in the tissue of upright stems, above or below the surface of the ground, such as bitterbrush *(Purshia tridentata)*, bigleaf maple *(Acer macrophyllum)*, rabbitbrush *(Chrysothamnus spp.)*, winterfat *(Ceratoides lanata)*, and mountain-mahogany *(Cercocarpus spp.)*. Bud masses may also be present in branch axils. Paper birch and madrone are species that have root collar buds located in stem tissue at the point where roots spread out from the base of the stem. Lignotubers, burls, and root crowns are names for masses of woody tissue from which roots and stems originate, and that are often covered with dormant buds (James 1984). Dormant buds may be deeplyburied in wood, and may be located far below the surface if the tissue mass is large. Chamise *(Adenostoma fasciculatum)*, serviceberry *(Amelanchier alnifolia)*, scrub oak *(Quercus dumosa)*, tanoak *(Lithocarpus densiflora)*, alder *(Alnus spp.)*, and mallow ninebark *(Physocarpus malvaceus)* all produce sprouts from these buried woody structures.

A caudex is an upright underground stem common in many forb species, such as arrowleaf balsamroot *(Balsamorhiza sagittata)* and lupine *(Lupinus spp.)*, that develops new leaves and a flowering stem each year. Other stemlike reproductive structures are bulbs and corms, which are essentially buried, short thickened stems with a bud or buds covered with fleshy leaves. Some species have dormant buds or bud primordia located along the surface of roots from which new shoots can originate, such as aspen, fireweed *(Epilobium angustifolium)*, and horsebrush *(Tetradymia spp.)*.

b. Postfire sprouting process. Postfire sprouting occurs by a very orderly process. The following discussion describes a likely model of the interactions that control postfire shoot development in woody plants. Similar processes probably regulate sprouting in grasses and forbs. The growth of most dormant buds or bud primordia of woody plants is controlled by a phenomenon called apical dominance. Growth hormones, particularly auxin, a plant hormone manufactured in actively growing stem tips and adjacent young leaves, are translocated to dormant buds, which prevent them from developing into new shoots (Schier et al. 1985). If these plant parts are removed, the source of growth hormones is eliminated. The balance of plant hormones within the buds changes (ibid.). Growth substances in roots, particularly cytokinins, that are translocated to the buds can cause dormant buds to sprout, or stimulate bud primordia to differentiate into shoots (ibid.). Cytokinins may already be present in buds, and a decrease in the ratio of auxins to cytokinins provides the stimulus for bud outgrowth (ibid.). The buds that become shoots are usually those nearest to the part of the plant killed by the fire. If dormant buds are destroyed, new buds may form in wound tissue, called callus, and subsequently produce shoots (Blaisdell and Mueggler 1956). Once new shoots are actively growing, they produce growth hormones that are translocated to other dormant buds that are farther away from the point of damage, suppressing their growth (Schier 1972; Bilderback 1974).

If the organic layer is thinned or disturbed, additional light may reach the tips of rhizomes and stimulate them to grow towards the surface and produce shoots (Barker and Collins 1963; Trevett 1956; Miller 1977). It has also been observed that decapitating a rhizomatous plant causes laterally growing rhizomes to turn upwards and become shoots (Schier 1983). Additional rhizomes often form in response to vigorous aerial plant growth (Kender 1967), which may subsequently produce aboveground shoots. Sprouts from new rhizomes or lateral roots may recolonize areas where all reproductive plant parts were killed by a fire. Plants may sprout soon after a fire, or not until the following spring if the fire occurs after the plants have become dormant for the winter (Miller 1978). Warmer soil temperatures after burning may enhance the amount of sprouting that occurs (Zasada and Schier 1973). The initial energy required to support growth until the sprout is photosynthetically self-sufficient comes from carbohydrates and nutrients stored in the reproductive structures or in adjacent roots (James 1984).

Postfire sprouting ability can vary with plant age. Young plants that have developed from seed may not be able to sprout until they reach a certain age, which varies by species (Smith et al. 1975; Tappeiner et al. 1984). For a given species such as bitterbrush, an older plant may be able to produce few, if any, sprouts that survive (Ferguson 1988). Other factors also may lead to decreased amounts of postfire sprouting in older bitterbrush. These include the higher amount of dead material within old crowns, and the deep organic layer found beneath some old plants that cause increased potential for lethal heating during a fire (Clark 1989; Miller 1988).

Aspen produces sprouts from healthy roots. Decreased amounts of postfire sprouting observed from older aspen stands (Schier 1975) may be because the condition of many of the roots has deteriorated to the point where they cannot sprout (Zasada, pers. conv. 1989). Aspen stands in Alaska can resprout vigorously after fire when they are 150 to 200 years old, perhaps because the incidence of pathogens in Alaskan aspen stands is relatively low (ibid.). In areas such as the Lake States, aspen stands are often killed by cankers by the age of 50 to 70 years (ibid.) An aspen stand that is producing a few understory suckers still has the capacity to sprout after a fire (DeByle 1988a).

Some plants therefore replace themselves, forming a new aboveground stem, but use essentially the same root system as before -- vegetative regeneration. Some plants may spread and develop new individuals from different locations along their roots or rhizomes. Shoots may form their own root system and become separate individuals. This is called vegetative reproduction by some, but these plants are genetically the same as the parent plant, and represent growth of the clone (Zasada 1989). True reproduction only occurs when a new genetic individual is formed, by establishment and growth of a new seedling (ibid.). Sexual reproduction of new individuals of gambel oak occurs when plants establish from seeds. Gambel oak can also regenerate vegetatively, replacing itself by sprouting from a lignotuber, and extending the clone by developing new plants from buds on rhizomes (Tiedemann et al. 1987).

c. Relationship of sprouting to burn severity. A strong relationship exists between burn severity, a measure of the amount of heating at and below the ground surface, and postfire sprouting in forested areas (Miller 1977; Dyrness and Norum 1983; Ryan and Noste 1985; Morgan and Neuenschwander 1988).

(1) A light severity fire occurs under moist fuel conditions, or where little fuel is present. Woody debris is partially consumed but some small twigs and much of the larger branchwood remain. Leaf litter may be charred or consumed, and the surface of the duff layer also may be charred. A light severity fire may kill reproductive parts at or very near the surface such as stolons, or stem buds that are not well protected by bark layers. It has little effect on most buried plant parts and significant amounts of postfire sprouting can occur.

(2) A moderate severity fire occurs when fine and smaller diameter dead fuels and surface litter and organic layers are dry, but large dead fuels and lower organic layers are still moist. Foliage, twigs and the litter layer are consumed. Duff, rotten wood, and much of the woody debris are removed. Logs are deeply charred. This type of fire kills or consumes plant structures in litter and in the top part of the duff layer, such as stolons and shallow rhizomes, and may kill buds on portions of upright stems that are beneath the surface, and buds on the upper part of root crowns. Sprouting occurs from buds in deeper duff or soil layers. Moderate severity fires frequently cause the greatest increases in stem numbers of rhizomatous shrubs (Miller 1976), and of root sprouters, such as aspen (Brown and Simmerman 1986).

(3) A high severity fire occurs when large dead fuels and organic layers are dry. It consumes all litter, twigs, and small branches, most or all of the duff layer, and some large diameter dead, down woody fuels, particularly rotten material. Significant amounts of soil heating can occur, especially near fuel concentrations. This kind of fire can eliminate plants with reproductive structures in the duff layer, or at the duff-mineral soil interface, and may lethally heat some plant parts in upper soil layers. Sprouting can only occur from deeply buried plants parts, which may still be a significant amount for species with deep roots such as aspen, or deep rhizomes such as gambel oak. Killing all belowground reproductive structures usually occurs only where there is a long duration surface heat source, such as beneath a large pile of woody debris that sustains almost complete combustion. Observations show that the concept of burn severity also can be related to fire effects on sprouting rangeland shrubs. The severity of burn relates to the depth of the litter layer beneath a shrub (Zschaechner 1985), and its moisture content when the fire occurs. A light severity fire may scorch litter beneath the shrub crown, but causes little or no damage to reproductive buds buried in stemwood or soil, although it can kill buds at the surface of the soil or those not protected by wood. Most sprouting plants will likely regenerate after this type of fire. A moderate severity fire consumes some basal litter and organic matter, and can kill some reproductive buds. Buds located in deeper litter layers may be lethally heated even if the litter is not consumed, and sprouting of some species may be reduced or eliminated. A high severity fire can consume all litter and organic matter beneath a shrub, and kills all buds and roots in or near the organic layer. This kind of fire favors shrubs with buds and roots buried so deeply in the soil beneath the plant that they do not receive a lethal dose of heat. Fires which occur where there are deep accumulations of litter beneath shrubs and isolated trees, or significant amounts of dead lower branches that burn off and smolder beneath a shrub crown, are more likely to lethally heat roots and reproductive structures than a fire that occurs where there is sparse litter and few dead branches. Reproductive buds of rangeland shrubs that are located on roots or rhizomes at some distance away from the parent plant are not likely to be killed by fire because fuels are often sparse in these locations.

d. Postfire sprouting of grasses. Grass meristems, growing points, are the point where new leaf tissue is formed during the active growing period, and resumes after summer quiescence or winter dormancy. New growth also may occur by "tillering," branching from dormant axillary buds in the plant crown or on rhizomes. Burning of all live leaves may stress the plant, and cause subsequent death. However, a more common cause of death of grasses is the lethal heating of meristems and buds. Sensitivity of meristems and dormant buds to heating relates to their location with respect to the soil surface and the fuel provided by dead grass and shrub litter, and other associated fuels, including shrub canopies. Meristems of some grasses form on long shoots which are elevated above the surface and are readily exposed to fire heat. Their postfire recovery depends upon growth form and whether any basal meristems and buds survive. A detailed description of the vegetative regeneration process in grasses can be found in Dahl and Hyder (1977).

Physiologically active meristems are more susceptible to heat than when they are dormant or quiescent (Wright 1970). Mortality of cool season grasses which green up early in the growing season can be caused by the burning of the litter of associated warm season grasses that are still dormant and hence more heat resistant. A high mortality of perennial grasses also may occur if fire burns in cured litter of annual grasses while perennials are still actively growing.

(1) Response of stoloniferous and rhizomatous grasses. Stoloniferous grasses, those which spread by stolons, such as black grama, are sensitive to heating. Many species of grass are rhizomatous, with meristems and buds buried beneath the litter, duff, or soil surface. Whether rhizomatous grasses are stimulated or killed by fire depends on rhizome location with respect to the surface, whether rhizomes are located in mineral soil or in organic layers, the moisture content of the litter, organic, and soil layers, and the amount and duration of heat generated by the surface fire. Rhizomatous grasses often respond positively to rangeland fires because meristems and buds are usually protected by soil, and a long-term surface heat source over large, contiguous areas is rarely present (Wright and Bailey 1982). In forested areas, grass rhizomes are more likely to be located in litter or duff layers or in association with dead woody fuels, and the potential for lethal heating is higher than it is in rangeland situations.

Litter and decomposed organic matter derived from rhizomatous graminoids such as cattails *(Typha latifolia)*, reeds *(Phragmites communis)*, and rushes *(Juncus spp.)* can accumulate to such thick levels that they completely fill areas of open water in wetlands. Occasional severe fire can have a criticalrole in maintenance of these wetlands. Fires which occur after long dry periods when water levels are low can consume much of this organic accumulation, restoring areas of open water. Prescribed fire is recognized as a management tool for this purpose in the Delta Marshes of Manitoba (Ward 1968). This same role in wetland maintenance for wildland fire has been noted in Alaska (Kelleyhouse 1980), and in the coastal plain of the southeast U.S. (Hermann et al. 1991).

(2) Response of bunchgrasses. The location of meristems and dormant buds of bunchgrasses can be near the surface of the bunch above the level of the soil, or at various depths below the soil surface within or below the bunchgrass litter. Buds and meristems can be readily exposed to lethal temperatures, or be fairly well protected if deeply buried in unburned organic materials or in soil. Fuel and moisture characteristics affect the amount of heat generated. Wright (1971) discusses the relationship between stem coarseness and the rate at which a bunchgrass clump burns. Fine stemmed grasses with a dense clumping of basal stems can burn slowly and generate a fair amount of heat that can be transferred to meristems and buds. Fire tends to pass fairly quickly through coarse stemmed bunchgrasses, which usually have little material concentrated at their base near reproductive structures. Fires tend to burn more rapidly through small diameter bunches in comparison to large diameter bunches, with larger bunches more likely to have enough fuel to release significant enough amounts of heat to affect growing points (Wright and Klemmedson 1965). The amount of surface litter, i.e., the amount of fine fuel, depends on the amount of use by livestock and wildlife, production in this and previous seasons, and the time since the last fire in areas receiving little utilization.

(3) Relationship of moisture conditions and fire behavior to mortality. The moisture content of fine aerial litter, accumulations of basal litter, dead bunchgrass centers, adjacent shrubs and shrub litter layers, and dead woody fuels all affect the amount and duration of heat that the meristems will receive. Mineral soil moisture can control how much heat is received by plant parts located in soil layers. While it is true that moist soil conducts heat better than dry soil, the moisture in surface soil layers must first be evaporated before heating of deeper layers occurs (Albini 1975 in Miller 1977). Moist heat, i.e., steam, may more effectively heat meristems than dry heat, and may be a cause of higher mortality when fires occur where greenup has begun in some plants. However, wet fuel doesn't burn, so the likelihood of a long duration fire under damp fuel and soil conditions that will kill all active bunchgrass meristems and dormant buds is very low, and heat penetration into organic and soil layers is minimal under these conditions (Frandsen and Ryan 1986). If flammable shrubs ignite, dry and preheat adjacent bunchgrass clumps, bunchgrass mortality may be higher than on a similar site with few shrubs that burned under the same conditions (Zschaechner 1985).

For a given litter moisture content, windspeed controls how quickly a fire passes over a plant and the rate at which the litter burns. Fires have been observed in northwest Colorado burning at windspeeds of 10 to 14 miles per hour (16 to 22.5 kilometers per hour) with rates of spread greater than 88 feet/minute (27 meters/ minute) during dry summer conditions. These fires charred only the tops of the crowns of bluebunch wheatgrass and Indian ricegrass plants that were 4 to 5 inches (10 to 13 centimeters) in diameter. Fire may have moved through grass litter too quickly to have a long enough residence time to ignite grass crowns, and little grass mortality occurred (Petersburg 1989).

(4) Relationship of damage to postfire sprouting. A fire may move quickly through a bunchgrass stand with little residual burning. At the other extreme, the dead center of a bunchgrass plant may ignite, smolder, and burn for hours. Conrad and Poulton (1966) developed damage classes for bunchgrasses: 1) unburned, although foliage may be scorched; 2) plants partially burned, but not within 2 inches (5 centimeters) of the crown; 3) plants severely burned, but with some unburned stubble less than 2 inches; 4) plants extremely burned, all unburned stubble less than 2 inches and mostly confined to an outer ring; 5) plants completely burned, no unburned material above the root crown.

Postfire response of a bunchgrass plant can be related to these damage classes, particularly for those species with meristems above the mineral soil surface (ibid.). The highest postfire sprouting potential usually is found in those plants with only some surface litter removed. The amount of sprouting tends to decrease as the amount of basal litter consumption increases, with new shoots most likely to appear from the outside edge of the bunch when little unburned stubble remains. Plant mortality is most likely if all plant material above the root crowns is consumed. Survival and recovery after a specific amount of fire caused damage must also be considered with respect to phenology and other seasonal factors that affect plant response. (See Sections B.4.a.; B.4.c.)

3. Seedling Establishment.

a. Seedbed. Requirements for successful germination and establishment vary for different species. Organic seedbeds, even rotting logs, may be able to successfully support seedling establishment and survival if water is not limiting during the growing season (Zasada 1971). However, moss, litter, and duff are poor seedbeds in many climates because they frequently dry out in the summer, killing the seedling if the root has not yet reached mineral soil. Other attributes of organic seedbeds may also inhibit seedlings (Zasada et al. 1983). For many species, the best seedbed is exposed mineral soil, and microsites where most or all of the organic layer has been removed by fire provide the greatest chance for seedling survival. Soil does not dry out as readily as organic material, and nutrients may be more readily available in ash. Competition from sprouting plants may be reduced.

On hot, dry, exposed sites, seedling germination and establishment may occur more readily if some organic material remains as mulch, especially if the seeds are covered (Clark 1986). Ponderosa pine seedlings are more likely to establish if seeds land on bare mineral soil, and the ungerminated seeds are subsequently covered by litter (McMurray 1988). Allelopathic chemicals, those that inhibit the germination and/or establishment of seeds of plants of other species, are commonly found in the litter beneath certain plant species, including chamise (McPherson and Muller 1969), Utah juniper *(Juniperus osteosperma)*, and singleleaf pinyon *(Pinus monophylla)* (Everett 1987a). Fire can volatilize these chemicals and allow additional seed germination. Some species that must establish from seed may be temporarily eliminated from a burned area because their establishment is not favored by conditions created by a fire. They may require shade, have slow growth of their primary root, or a high water requirement. Some tree species such as pinyon and juniper, may establish a few years after a fire in the shade of plants that established first, but subsequently can grow in full sun (Everett 1987b).

b. Seedbank. The seedbank, the supply of seeds present on a site, is composed of buried seeds, those stored in the tree canopy, and those that are deposited annually. Seeds of some species, such as willow, are very short-lived, and are part of the seed bank for only a short time. Other species have extremely long-lived seeds, and become a fixed member of the soil seedbank, once their seeds are dispersed.

Seed dispersal mechanisms vary. Light seeds may be windblown while heavier seeds may skid across the surface of the snow. Some seeds have wing-like structures which enhance their movement through the air. Seeds with barbs or hooks may be carried by animals. Hard-coated seeds ingested along with their fruit may pass through the bird or animal, with an enhanced likelihood of germination. Seed dispersal from unburned areas depends on the amount of available seed, the distance of the seed source from the burned area, the prevailing wind direction, and the type of seed.

The supply of seeds of a specific species can be greatly influenced by the amount of annual seed production, which can vary significantly (Zasada et al. 1978). Regeneration of conifers may be limited because cone crops are poor during the period of time when exposed mineral soil seedbed is present.

Surviving plants on or near the burned area may not be old enough to produce seed (Zasada 1971; Barney and Frischknecht 1974), or may be too old to produce much viable seed.

The dispersal of seeds from plants occurs at a time that is characteristic for that plant, and can last for different durations of time (Zasada 1986). The time of fire occurrence with respect to seed dispersal can determine whether a species can regenerate promptly. Heat from the fire may kill seeds in the canopy and seeds that have recently been distributed onto the site. Seeds of a certain species may require a period of cold before they can germinate, so seedlings of that species will not appear until the following spring.

Seeds in immature cones in tree canopies may have survived the fire, and may continue to ripen even though the foliage was killed (ponderosa pine) (Rietveld 1976), or the bole was completely girdled by fire (white spruce) (Zasada 1985). Serotinous lodgepole pine cones retain their seeds because of the presence of a resin bond between the cone scales. These cones do not open and release their seeds unless heated to 45 to 50C (113 to 122F), a temperature that melts the bond (Lotan 1976). Numerous lodgepole pine seeds are often released after heating of the canopy during a fire. However, there is considerable variation in the amount of cone serotiny, both on individual trees, and geographically (ibid.). Black spruce *(Picea mariana)* cones are "semi-serotinous", i.e., they open and release their seeds over a period of years (Zasada 1986). Because cones are usually bunched near the top of the tree, some cones are often shielded from fire heat and provide a postfire seed source.

c. Stimulation of buried seed. There may be an enormous reserve of seed stored in litter, duff, and soil. Seed may accumulate on the surface and be gradually buried by litter, or may be cached by rodents and birds (West 1968; Tomback 1986). Seed of some species may remain viable for many years, with dormancy imposed by an impermeable seed coat (Stone and Juhren 1953). Plants such as snowbrush ceanothus *(Ceanothus velutinus)*, raspberry *(Rubus idaeus)*, geranium *(Geranium bicknellii)*, and corydalis *(Corydalis sempervirens)*, as well as many annuals of California chaparral may appear on a site after a fire where they were not apparent before the fire. Seeds of snowbrush ceanothus remain viable for 200 to 300 years (Gratkowski 1962 in Noste and Bushey 1987). Germination of some species is enhanced by fire that can melt or crack the seed cuticle or otherwise scarify the impermeable seed coat (Keeley 1987; Rasmussen and Wright 1987).

Requirements for optimum germination may be very specific, such as redstem ceanothus that has the highest amount of germination after exposure to moist heat at 80 C (176 F) (Gratkowski 1973), explaining its higher germination after high severity fires than low severity fires (Leege 1968). Chemicals leached from charred materials stimulate germination of many species of California chaparral and coastal sage scrub (Keeley 1987). Increased light levels caused by removal of vegetation can induce or enhance seed germination (Keeley 1987). Some species, such as chamise and hoaryleaf ceanothus *(Ceanothus crassifolius)*, produce a certain proportion of seeds that will only germinate after fire treatment, while other seeds from the same plant will germinate under any suitable moisture and temperature conditions (Christensen and Muller 1975a). Annual species may appear from stored seed after a fire, but may disappear in a few years as site conditions change, a common phenomenon in California chaparral (Sweeney 1956; Muller et al. 1968; Christensen and Muller 1975b).

Germination of seeds of chaparral communities is adapted to wildfires that normally occurred during fairly hot, dry, late summer or fall conditions. Seeds of some species of chaparral communities require dry heat to induce germination, but are killed by lower temperatures if they have imbibed moisture. Other seeds require higher temperatures for a longer duration to induce germination than generally occur under spring burning conditions (Parker 1989). If chaparral sites are burned under moist spring conditions, germination of both of these types of seeds is often very much reduced. This is a particular concern for maintenance of a seed bank of chaparral "fire-following annuals" as well as shrub species that can only reproduce from seed (Parker 1987).

d. Dual response plants. Some plants will recover after a fire both by resprouting and by germination of duff stored seeds, while obligate seeders reproduce by seed only. Obligate seeders often have seedlings with better potential for establishment than seedlings from species that sprout (Parker 1984). Other plants have a two-stage response to fire. They sprout from surviving reproductive structures, then produce seed, right onsite, that can readily utilize available seedbed. Fireweed and rabbitbrush, for example, can sometimes gain temporary dominance over a site for these reasons.

4. Factors Influencing Postfire Plant Recovery and Growth.

a. Climate and weather. Different parts of the country have characteristic seasonal distribution of temperature and precipitation. The overall pattern of seasonal plant growth (phenology) relates to climate, such as the time of the year when most growth occurs; occurrence of late summer quiescence, and the onset of winter dormancy. However, the timing and rate of plant development and total amount of growth can vary greatly with seasonal weather (Mueggler 1983). The date when plants begin growth, flowering, and cease growing all relate to seasonal weather (Sauer and Uresk 1976). The average annual occurrence of the wildfire season in various parts of the country is closely related to climate, while the actual timing and severity is related to fuel amount and conditions, and the weather that occurs that year. Generalizations can be made about weather trends and patterns for a particular region, but there are always exceptions. Long-term averages do not reflect the wide range of conditions possible.

(1) Prefire weather. Prefire weather can affect the plant growth stage at the time of burning. The amount and availability of fuel is influenced by weather. Fires in the cheatgrass region tend to be much larger in years with high winter precipitation and spring rain, resulting in high production of fine fuel. Burned acreage in the Sonoran Desert tends to be higher after two winters of above average precipitation that promotes growth of winter annuals, which subsequently dry and provide fuel (Rogers and Vint 1987). The moisture content of heavy fuels and deep litter and duff layers is closely related to temperature and precipitation in previous months, and thus the likelihood that these fuels are available to burn and provide a long-term heat source is weather dependent (Brown et al. 1985). Fire size, and its degree of impact on vegetation, is influenced by fuel availability, and burning conditions at the time of the fire. Drought, anomalous high winds and low humidity, or high summer precipitation all affect the immediate impact of a fire in a particular area in a certain year.

(2) Postfire weather. Postfire weather can affect plant survival. Sprouting plants must produce enough growth to restore food reserves before the next period of high use, and this growth can be enhanced or limited by weather. Without restoration of carbohydrate reserves, the plant may die. Plants which sprout late in the season also can die because they have too little time or energy to harden off for the winter. The amount of autumn rain can determine whether germination of seed of some species occurs in the fall or the following spring. Late summer rains (Thill, Beck, and Callihan 1984) followed by a dry period can cause germination, and subsequent death, of many seedlings. Weather in the following years affects the rate of recovery from burning by influencing productivity. Drought can place additional stress on injured plants, and increase the likelihood that they will die. Postfire weather is a primary factor in determining range readiness for postfire grazing use. The weather cannot be controlled, but it is important to document it. Fires burned on similar sites in different years with the same burning weather may have widely varying results because of differences n prefire and postfire weather. Analysis of these records may explain the reasons for significant variations in postfire response, and the "success" or "failure" of a specific prescribed fire project.

b. Carbohydrates.

(1) Carbohydrate cycle. Carbohydrates are starches and sugars manufactured by plants and used to provide energy for metabolism, and structural compounds for growth (Trlica 1977). Carbohydrates which are manufactured in excess of those used are stored in various parts of the plant, such as roots, rhizomes, root crowns, stem or leaf bases (Cook 1966a), or evergreen leaves. There is a seasonal cycle of depletion and restoration of total available carbohydrates (TAC) that relates to events in the growth cycle of the plant. The most rapid depletion usually occurs during greenup, to support initial development and growth of leaves and shoots. Stored carbohydrates levels also may be lowered during the period of flower and fruit development. Carbohydrates are required to prepare plants for winter, the "hardening off" process, as well as for respiration and cellular maintenance during winter dormancy (McCarty and Price 1942 in Trlica 1977), and quiescence during late summer drought conditions (Hanson and Stoddart 1940 in Trlica 1977). Roots must be maintained even while the aboveground part of the plant is not actively growing. A major depletion also can be caused by heavy or repeated grazing or browsing, as the plant may need to use reserves to support subsequent new growth if inadequate leaf area remains on the plant to provide energy for growth and new tissue formation. "In general, too heavy, too early, or too frequent grazing or defoliation result(s) in declining vigor of vegetation" (Hedrick 1958 in Trlica 1977).

Restoration occurs when production by photosynthesis exceeds demands for growth and respiration. The beginning and length of the restoration period varies. Cook (1966a and b) discusses the seasonal carbohydrate cycle. Some plants rapidly deplete, but then quickly restore carbohydrate reserves, all within about the first month of growth. Squirreltail *(Elymus elymoides)* is a plant that exhibits this V-shaped carbohydrate cycle. U-cycles are shown by plants that deplete carbohydrate reserves over a much longer period of time, and don't begin to make a significant restoration of reserve carbohydrates until later in the growing season. Bitterbrush, a species with a U-cycle, does not show a major increase in its level of reserves until August or September, only accumulating carbohydrates from the period of seed formation until leaf fall (McConnell and Garrison 1966). The timing of highs and lows in the carbohydrate cycle thus corresponds with the growth states of the plant. The cycle can differ from year to year because the timing of phenological events can vary significantly among years (Sauer and Uresk 1976; Schmidt and Lotan 1980; Turner and Randall 1987). The amplitude of the cycle will vary with growing conditions, the amount of growth produced, and the amount of carbohydrate used for other physiological processes, all of which affect the amount left for storage.

(2) Relationship to fire. Energy and material for initial plant regrowth after a fire depend on the availability of reserve carbohydrates. The biggest negative impacts from burning may occur during the lowest point in a plant's annual carbohydrate cycle, usually during the early seasonal growth period. The low survival of chamise sprouts after spring prescribed fires has been attributed to low winter and spring carbohydrate reserves because of high spring demand for growth, flowering, and fruiting (Parker 1987). For other species, the effects are most negative if the plant is burned late in the growing season when reserves are being rapidly replenished because the plant uses a considerable amount of stored carbohydrates to sprout, but does not have enough time to restore reserves before winter dormancy (Trlica 1977; Mueggler 1983).As a result of burning during an unfavorable growth period with respect to stored carbohydrates, a plant or any sprouts that it produces may die during the next long period of carbohydrate demand, such as summer quiescence or winter dormancy. If the plant survives, its productivity in the next few years may be greatly reduced. An additional consideration when burning old stands of woody plants is that energy reserve levels of these plants may be low, because annual production is low, and/or much of the plant's carbohydrate production is used to maintain old plant tissue. Meager amounts of sprouting observed from old bitterbrush plants may be partially due to low levels of stored root carbohydrates.

The degree of dependency for regrowth that a plant has on carbohydrate reserves after fire depends on whether any photosynthetically capable material, such as sheath leaves on stubble, survived. If some plant tissue that can photosynthesize remains or rapidly regenerates, newly grown leaf material soon manufactures all of the carbohydrates that the plant needs for growth and respiration. However, the initial spurt of growth after a fire likely requires use of some stored carbohydrates, even if only for a day or two. Evidence from clipping and grazing studies has shown that the recovery of grass plants is more related to the removal of growing points than to the carbohydrate level at the time of defoliation (Caldwell et al. 1981; Richards and Caldwell 1985). However, fire may have a greater impact on grass plants than severe defoliation because a majority of the carbohydrates used to initiate regrowth are derived from the basal portion of the older tillers, and these may not survive a fire.

c. Postfire plant competition. Plant competition occurs when growth and reproduction of one plant is hampered by the presence of another, or, when the resources of a site required by one plant are reduced by another (Harris 1977). Plants compete the most for whatever is in shortest supply - particularly water, nutrients, and light. Whether competition occurs and the degree to which it occurs depends on the species present on the site, the number of plants present, and the site conditions (Samuel and Depuit 1987; Brand 1986). Simultaneous requirements for limited resources such as water and light can place individuals in competition with each other. Whether certain species compete depends on the timing of germination and growth, germination and establishment requirements, rate of growth, and requirements for water and nutrients. Some species have an innately high ability when in a seedling state to compete with seedlings of other species (Samuel and DePuit 1987). The ability of a plant to respond to changes in the supply of nutrients or water varies by species (ibid.). Some species can take better advantage of changes in the postfire environment than other species can, which may give them a competitive advantage.

Fire affects plant competition by changing the numbers and species of existing plants, altering site conditions, and inducing a situation where many plants must reestablish on a site. In a postfire situation established perennial plants that are recovering vegetatively usually have an advantage over plants developing from seed because they can take up water and nutrients from an existing root system while seedlings must develop a new root system (ibid.). Natural regeneration of shrubs may severely limit growth of naturally occurring or planted conifers because of competition for light or moisture (Stein 1986; Haeussler and Coates 1986). If perennial plants are few, or their postfire survival is low, and a seed source is present, seedlings may establish and dominate the community for varying periods of time. Certain species may be favored, such as ceanothus (Parker 1984), because of the sheer volume of seeds on a site. Cheatgrass *(Bromus tectorum)* has such a great postfire advantage over seedlings of most native grasses because roots of cheatgrass seedlings can grow at much cooler soil temperatures than those of most native perennial grasses, and can proliferate much more rapidly at warmer soil temperatures than can roots of natives. Cheatgrass seedlings can deplete soil moisture in the spring before other species get their roots down into the soil profile (Thill, Beck, and Callihan 1984).

Grass seeded for postfire erosion control in forested areas may easily overtop conifer seedlings. In chaparral areas, seeded grasses compete with sprouts and seedlings of native plants (Barro and Conard 1987). Litter from seeded grasses may increase the flammability of these sites to higher levels than would occur if only native vegetation recovered on the site (Cohen 1986 in Barro and Conard 1987). A second fire after a short time interval might kill all seedlings of native species, often before they have produced much seed, decreasing the number of seeds in the soil seed bank. Conversely, if seeded crested wheatgrass establishes on a cheatgrass site after it burns, the amount of litter, and fire frequency, can decrease.

A lack of fire can also increase plant competition. One hundred year old stands of juniper usually have very low cover of shrubs and grass (Barney and Frischknecht 1974), probably because of juniper's superior ability to extract soil water, as well as the inhibitory effect of juniper litter on germination and establishment of seedlings of shrub and herbaceous species (Everett 1987b). Herbaceous production in the vicinity of sagebrush plants decreases as sagebrush cover increases, because of root competition (Frischknecht 1978). Young stands of conifers that develop in the absence of fire beneath mature overstories of ponderosa pine compete for moisture and nutrients with the mature trees (Wyant et al. 1983), weakening them and making them susceptible to insects and disease.

d. Animal use. If burning occurs in close association with heavy use of the plant community by livestock or wildlife, either before or after the burn, plant recovery may be delayed or prevented. Heavy postfire use of perennial plants in the first growing season after a fire is likely to cause the most harm, particularly in arid and semiarid range communities (Trlica 1977). Depending upon the plant community and its production capabilities, some use after the first full growing season may not have a negative impact, and may even be desirable, as in tobosagrass communities. Two full growing seasons of postfire rest are necessary before plants can sustain much utilization in the Intermountain west after wildfire (Wright and Bailey 1982). A longer recovery period is necessary if weather has been unfavorable for growth, or if establishment of plants from seeds is required to completely revegetate the site. Desert plants required more than seven years of recovery after moderate defoliation (Cook and Child 1971 in Trlica 1977), and some shrubland sites may require this long a period of postfire rest if recovery of browse species is desired. See Chapter IX.B.2 and B.3 for additional discussion on this topic.

5. Plant Productivity. Fire can affect postfire plant productivity. Short-term decreases can be caused by plant mortality, reduction in basal area of grasses, forbs, and shrubs, changes in species composition to less productive plants, and reduced availability of soil nutrients. Increases are caused by fire induced vegetative reproduction and regeneration, fire enhanced seedling germination and establishment, improvements in the soil nutrient regime, and increases in soil temperature. Warmer soil temperatures often result in earlier greenup on burned areas, particularly in grassland and rangeland environments.

Removal of thick layers of litter and organic matter in tall grass, wetland, and boreal environments increase soil temperature and nutrient availability, enhancing plant growth (Vogl 1973 and Hulbert 1969 in Young 1986). An occasional fire is very important for rejuvenating cold, nonproductive forest sites in interior Alaska (Yarie 1983), and this is likely also true for many tundra sites. Where permafrost is present, many nutrients are tied up in frozen organic layers, and are unavailable to plants (Heilman 1966; 1968). Fire's removal of insulating organic matter and the blackened surface cause deeper annual soil thawing, and a greater depth and higher temperature of the rooting zone. Soil acidity decreases and rates of nutrient cycling increase. Vegetatively regenerating plants and seedlings use these nutrients, significantly enhancing growth. Eventually, organic matter accumulates and becomes an effective soil insulator, causing a decline in both growing season soil temperatures and associated plant productivity.

There may be a significant decrease in productivity during the initial postfire recovery period, then an increase in production after one or several years. Some conifers have reduced growth the first growing season after the fire, but show increased growth rates in subsequent years caused by the removal of competing trees (Reinhardt and Ryan 1988a). Total productivity may not change, but can shift among classes of plants on the site, such as from conifers that are killed by a fire to shrubs, grasses, and forbs (Volland and Dell 1981). Total site productivity may actually decrease, but production of shrubs, grasses, and forbs often increases over prefire levels (Harniss and Murray 1973; Dyrness and Norum 1983). On sagebrush sites, total prefire productivity may not be reached until sagebrush again dominates the site (Bunting 1985), because its deep root system can allow it to utilize site resources that are physically unavailable to other plants.

The length of productivity changes depends on the ecosystem, the degree of change caused by burning, and the resulting amount of change in species composition in the postfire plant community. A low intensity, low severity fire may have little effect, while a shift from an old coniferous forest to a shrubfield may result in long-term changes in plant production. Site productivity in the first few years after fire will likely be higher if a significant amount of vegetative regeneration occurs, than if plants on the site must reestablish from seed. Sprouts can obtain nutrients and carbohydrates for initial growth from the parent plant while a seedling often has access to only a small nutrient reserve in seed, and may initially grow fairly slowly. Seedling establishment and growth are much more dependent on site conditions and postfire weather. Snowbrush seedlings grow slowly until age 4 or 5, but then grow rapidly until about age 10, while sprouts of snowbrush may grow from 1 to 2 feet (0.3 to 0.6 meters) per year from the time growth is induced (Peterson 1989). Exceptions to this general rule do occur. Obligate seeders, plants that must regenerate from seed, can be adapted for making rapid growth on burned or disturbed sites (Parker 1984).

Greatly increased amounts of flowering and fruiting may occur, including a significantly enhanced output of grass seed and berries (Daubenmire 1975; Young 1986; Christensen and Mueller 1975b). Changes in production are caused by the same factors that increase vegetative productivity: warmer soil temperatures, improved nutrient availability, and removal of senescent, woody material that requires a lot of energy to maintain. For a given species, flower and fruiting generally occur sooner on sprouts than on plants that develop from seed. For some species, flower buds are formed on the previous year's growth, so it takes two growing seasons for flowers and fruits to appear. Increased levels of fruit or seed production may only persist for a few years of burning. Improvements in forage amount and availability, and increases in flowering and fruiting are key reasons for wildlife and livestock attraction to newly burned areas.

C. Resource Management Considerations

Fire effects on plants cannot be understood unless their survival and reproductive strategies with respect to fire are understood. Some plants resist fire by characteristics such as thick bark or buds that can withstand scorching temperatures. A site can be repeatedly burned, and many of these plants survive. Plants may have their surface parts completely consumed, but endure the fire because belowground reproductive structures typically survive. Some plants are almost always killed by fire, and their seedlings cannot tolerate immediate postfire conditions. It can be said that these species avoid fire, because they are only found on sites that are fire-free for long periods of time (Rowe 1983).

Plants can be divided into four basic groups with respect to postfire revegetation of a site (Stickney 1986), as defined by their source and time of establishment. Survivors are species with established plants on the site that can regenerate after a fire. Colonizers are species that establish on the site from seed. Residual or onsite colonizers originate from seed that is present on the site at the time of the fire. Off-site colonizers develop from seed that is carried from off the site. Secondary off-site colonizers develop from off-site seed, but not until site conditions are mitigated by the plants that established first. Initial establishment of a plant is only the first step, because its long-term survival and productivity is affected by competition with other plants and by weather.

The following management considerations summarize key elements to consider with respect to predicting, observing, and interpreting the effects of fire on plants. They are derived from information explained in greater detail in the text of this chapter, as well as in Chapter II. Fire Behavior and Characteristics, and Chapter III. Fire Effects on Fuels.

1. Plant Mortality.

a. Relationship to fire behavior, fire characteristics, and fuels.

(1) Flame length relates to the amount of crown scorch and canopy consumption.

(2) Dry concentrations of down, dead woody fuels can ignite and provide a long-term heat source that can damage a tree crown, tree stem, roots, or buried reproductive structures.

(3) The amount of heating that results from combustion in the flaming front of a prescribed fire can be regulated. Ignition methods and techniques must be selected with consideration for fuel conditions, weather, and slope steepness and concavity.

(a) The width of the flaming zone can be manipulated by controlling the number of lines of strip headfires that are ignited at once (Norum 1987), and the spacing between them.

(b) Regulating the interval between lines of strip headfires controls flame length, because the shorter the interval between lines, the shorter the flames (ibid.)

(c) Use of rapid ignition techniques can greatly increase the rate of heat release and decrease the duration.

b. Crown scorch height.

(1) The height to which tree crowns are being scorched is often not obvious during ignition of a prescribed fire.

(2) Scorch height can be estimated from current weather, and observed flame lengths, using the graphs in Albini (1976, pages 63 to 66).

(3) If scorch height is too high, then ignition can be altered to lower flame lengths, or the fire may be curtailed until more moderate burning conditions occur.

(4) Too high a scorch height can indicate that the fire prescription may require modification to reduce scorch heights, such as by prescribing increased fuel moistures, or lower air temperatures when the fire is ignited.

c. Mortality of crowns.

(1) Dormant buds have varying degrees of sensitivity to fire heat. Sensitivity relates to size, the presence of protective bud scales or needles, and whether they are physiologically active or dormant.

(2) Foliage flammability and sensitivity to scorching temperatures varies seasonally, especially because of changes in foliar moisture content.

(3) Foliage flammability varies by species according to branch density, the presence of lichens, presence of flammable compounds, retention of ephemeral or evergreen leaves or needles, and the proximity of the crown base to the surface of the ground.

d. Mortality of tree stems and cambium.

(1) Thick barked species are more resistant to fire heat than thin barked species.

(2) Duration of heating is generally more important than peak temperature in determining damage to thick barked trees and shrubs.

e. Mortality of roots and other buried reproductive plant parts.

(1) Potential for heating to lethal temperatures relates to the plant part and its location.

(a) Depth of roots or reproductive structures below the surface.

(b) Whether plant parts are located in litter, soil organic layers, or mineral soil.

(2) The potential for heating relates most closely to the duration of heat released during the consumption of accumulations of dead woody fuels or deep litter and duff layers. Duff reduction relates to its moisture content (Norum 1977; Brown et al. 1985). See Chapter III.B.3.a. for moisture content guidelines for consumption of organic soil layers.

(3) Moist soil retards the penetration of heat and protects buried plant parts.

2. Postfire Sprouting.

a. Process. The physiological processes that control postfire sprouting are essentially the same for trees, shrubs, forbs, and grasses.

b. Species specific characteristics. The type of plant part on which dormant buds are located, the subsurface distribution of reproductive structures, and the depth below the surface from which new shoots can develop are species specific characteristics.

c. Relationship to burn severity. Sprouting is closely related to burn severity because the number of postfire sprouts relates to the number of reproductive buds or bud primordia that survived the fire. A species may be enhanced or harmed depending on how deeply lethal temperatures penetrated below the surface, and the characteristic depth of its reproductive structures.

d. Spread from adjacent areas. On sites where all reproductive structures were killed, sprouts may develop from rhizomes or roots that colonize the area from adjacent, less severely burned areas.

e. Bunchgrasses. Bunchgrass species also have reproductive buds located at characteristic depths below the surface, and with respect to accumulations of dead basal material.

(1) Moisture contents of basal litter, dead centers of plants, and soil are critical for determining the amount of consumption of a bunchgrass plant.

(2) There is a potential for additional heating of bunchgrasses from burning of adjacent shrubs, with the amount of heat related to shrub species, density, and flammability.

(3) The amount of consumption of a bunchgrass plant of a particular species can be related to its potential for postfire sprouting, because it relates to the amount of physical damage to growing points and dormant buds.

3. Postfire Reproduction by Seed.

a. Seed ecology. The likelihood that a species will reestablish from seed depends upon its seed ecology.

(1) Germination and establishment requirements.

(2) Whether its seed is sensitive to heating or is stimulated by heat or chemicals leached from charred materials.

(3) Length of period of seed viability.

b. Seed source.

(1) Distance from living, seed producing plants.

(2) How much seed in organic and soil layers survived the fire.

c. Timing of fire.

(1) Production of current year's crop of seeds.

(2) Age of plants on or near the site, whether they were old enough to produce seed.

d. Soil seedbank. Some species of plants may establish from duff or soil stored seed and produce a significant amount of biomass.

(1) The length of time that a species persists depends on its habitat requirements and how the site conditions change as plant succession proceeds.

(2) Different plant communities have characteristically different species and numbers of seeds in their seed bank, that also vary in longevity.

e. Relationship to burn severity.

(1) The amount of bare mineral seedbed created.

(2) The amount of heat stimulation or mortality of specific species.

4. Carbohydrates.

a. Plant phenology. Plant growth stage is related to the level of stored carbohydrates that provide energy for initial postfire vegetative regrowth.

(1) The amount and timing of high and low levels, and rates of recovery, of stored carbohydrates varies by species, and with conditions in a particular growing season.

(2) Recovery of a plant may be most affected if a plant is burned during a low point in its carbohydrate cycle, or when there is not enough time for the plant to rebuild stored carbohydrate levels before the next period of high demand.

b. Animal use. Prefire and postfire use of a site by livestock and/or wildlife must be evaluated and managed, particularly important if heavy utilization has occurred.

5. Postfire Plant Productivity.

a. Tree growth. Postfire productivity of surviving trees relates to the amount of injury to crowns, stems, and roots.

b. Sprouting woody plants. Rapid recovery of perennials may occur by postfire sprouting if reproductive structures were not killed.

c. Seed and fruit production. Seed and fruit production generally increase much more quickly from plants that regenerate vegetatively, than from plants that must establish from seed.

6. Direct Seeding and Planting.

a. Postfire rehabilitation considerations.

(1) The requirement for seeding is determined by the specific situation on the burned area and the management objectives for the area. Factors such as erosion control, native species restoration, limiting establishment of annual exotics, and meeting wildlife habitat requirements are major considerations in the decision whether or not to do postfire rehabilitation.

(2) The likelihood of survival of native species should be assessed before artificial reseeding is planned. The percentage mortality of individual plants should be estimated, and likely methods of recovery determined, such as vegetative regeneration or plant establishment from stored seeds. (See B., this chapter.) Reseeding is not necessary where recovery of native plants will occur.

(3) Prefire species composition may be determined by inspection of adjacent unburned areas. A seed mixture of species adapted to the site results in the highest likelihood of establishment, as well as the greatest long-term diversity and productivity. Grass, forb, and shrub mixes have been successfully seeded on some Federally managed rangelands.

(4) Seeded grasses may compete with other desirable species.

i. Seeded grasses can interfere with the establishment of native plants, and limit the future seed bank of those species.

ii. Seeded grasses can provide significant competition to planted trees and shrubs.

iii. Where postfire erosion is a significant threat, seeding annual or short-lived perennial grasses may allow greater recruitment of native plants than seeding long-lived perennial species.

b. Need for rapid replanting. It is often necessary to plant tree seedlings on productive sites as soon as possible after fire because of potential competition from naturally regenerating shrubs, grasses, and forbs. Rapid reseeding of rangeland sites is required if an objective is to establish perennial species on a site dominated by annual exotics.

c. Prescribed fire considerations.

(1) Residual logs and duff can enhance site productivity by providing sites for mycorrhizal infection, and nitrogen fixation, both of which are beneficial to establishment and growth of tree seedlings. (See V.B.c.(4) and (5), this Guide.)

(2) Residual downed logs and shade from standing dead trees provide shade that can aid establishment of planted seedlings or natural regeneration on dry forest habitat types.

7. Effect of Postfire Weather. Postfire weather has a significant effect on the rate and amount of postfire vegetative recovery.

8. Need for More than One Treatment.

a. Dual treatment. A site may require burning after mechanical, chemical, or manual treatment to kill residual target species or seedlings developed from residual seed.

b. Maintenance burning. Repeated burning at regular intervals may be necessary to prevent reinvasion of the site by seedlings of undesired species. The desired burning interval is related to the natural regime that fire used to play in the vegetation community on the site.

D. Methods to Monitor Fire Effects

A variety of monitoring methods have been employed to study vegetative attributes and their changes over time. Those methods most appropriate for postburn studies will be reviewed here. Monitoring schemes chosen to evaluate the effects of fire on both individual plants and plant communities must be sensitive to the responses observed from the perturbation of burning. If the fire has been planned, methods selected by the observer to evaluate changes in the vegetative component must necessarily follow the objectives of the fire so that the vegetative responses can be properly evaluated. Preburn measurements are critical, and thoughtful establishment of almost any preburn study will provide valuable information.

Specific attributes of vegetation or plant communities affected by fire may be expressed in the generally accepted terms of cover, density, frequency of occurrence, weight, species composition, number, height, vigor, growth stages, age classes, and phenology. Plant mortality, injury to trees, and burn severity, all a direct function of burning, also merit consideration because they directly or indirectly relate to postfire effects. Definitions of each of these attributes will be given as monitoring methods appropriate for each are discussed.

In addition to selection of the most appropriate methods of study, two other considerations are vital for a successful monitoring program: control plots must be established outside the area of the fire so that universal factors that may be influencing results, such as climate or insect infestations, can be separated from effects of the fire itself; and, timing of studies must be planned so that plants have reached maximum growth, and repeat studies should be taken as near to the same time as possible as the initial studies were conducted. For planned burns, control plots must be in similar vegetative communities as the area to be burned in order to make valid conclusions regarding fire effects.

Standard references discussing both the philosophy and methodology of vegetation sampling include Cook and Stubbendieck (1986), Greig-Smith (1983), Mueller-Dombois and Ellenberg (1974), Pieper (1973), and Brown (1954). A rangeland monitoring guide describes in detail the more commonly used techniques for monitoring range trend, some of which may be valuable in monitoring fire effects (USDI-BLM 1985a). Additional guidance for prefire and postfire vegetation monitoring is found in USDI-NPS (1992).

The matrix in Table VI-1 relates the specific effects of fire on vegetation to measurable vegetation and site attributes, so that appropriate methods of study can be most efficiently chosen for the effects to be measured. In designing any sampling scheme, the community type being sampled must be considered in determining which methodology to be employed, as well as size and shape of plots to be used. Chambers and Brown (1983) outline appropriate quadrat sizes and shapes for specific methodologies in a variety of vegetation types. It is important to work with qualified personnel to design valid sampling schemes and methods of analysis. (See Chapter XI, this Guide, for a discussion of sampling and statistical analysis.)

1. Cover. Cover refers to the area on the ground covered by the combined aerial parts of plants expressed as a percent of the total area. Specifically measured are either basal cover, which is the vertical projection of the root crown on to the ground, or foliar cover, which includes the projection of all plant parts vertically on to the ground. Cover of litter, rocks, or any other physical parameter on the ground may be determined using cover measurements.

Points and point frames are also used to measure cover (Chambers and Brown 1983; Floyd and Anderson 1983), and are particularly suited to dense or rhizomatous vegetation where intensive sampling is desired. A disadvantage of using points is that an extremely large number of points must be collected to obtain a representative sample of the population. Specific methods include vertical and inclined point frames, points along line transects, and pace transects. First hit only or all hits through the various canopies may be recorded. Usually, aerial canopy is used for trees, shrubs and broadleaf perennial forbs, and basal crown is used for grasses and single-stemmed forbs. Where vegetation is identified by layer, cover may exceed 100 percent. Cover using quadrat frames has been employed by Daubenmire (1959). The method uses canopy coverage classes for each species within a given frame.

Table VI-1: Vegetation and Site Attributes Useful for Evaluating Selected Fire Effects.

FIRE EFFECTS

ATTRIBUTES	Mortality	Reproduction		Productivity	Structure
		Sprouts	Seedlings		
Cover	I*			I	D
Density	D**	D	D		
Frequency	I	I	I		
Weight	I			D	
Species Composition	D		D		I
Number	D				D
Height				I	D
Crown scorch	D/I***	I***		I	
Crown consumption	D***	I***		I	D/I
Stem char	D/I***	I***			
Burn severity	D/I***	D/I***	I	I	D/I

* I = Indirect Relationship
** D = Direct Relationship
*** = Depends upon species

2. Density. Density is the number of plants or parts of plants per unit area, although older literature may use the term to refer to the attribute of cover. Density is highly useful and frequently used for evaluating effects of fire on mortality and reproduction. It is generally straightforward, easily measured and readily understood. Density is not particularly useful in describing community structure and the relationship of species importance to one another, but can be highly valuable in tracking response of individual species to fire. For example, the methodology may measure the number of seedlings, shrubs, or trees per unit area. Response of rhizomatous or suckering plants, such as Western wheatgrass or aspen, may be measured in terms of stems or ramets per unit area with this methodology also. Sprouting shrubs are often tracked using density measurements before and after controlled burning.

Quadrats used to sample density may be small frames or large plots, depending on size and abundance of the species studied. Species to be monitored must initially be defined; size of plots will follow so that the physical sampling does not become cumbersome. Belt transects to measure density of shrubs before and after burning are frequently used in rangeland situations.

3. Frequency of Occurrence. A quantitative expression of the presence or absence of individuals of a species in a population is termed frequency of occurrence, or simply frequency. It is the ratio between the number of sample units that contain a species and the total number of sample units. Its sensitivity in accurately reflecting the population parameters is a direct function of the size of the quadrat used for sampling. Because this method does not measure any plant or plant community attribute directly, its usefulness in fire management has been somewhat limited. Frequency is an integrator that encompasses plant size and shape, density, distributional patterns, number, and a host of other physical attributes. Because of the often severe nature of fire's effects on a plant community, wide swings in frequency values may present problems in both sampling and interpretation of results.

Quadrat sizes used to sample frequency will vary based on vegetative characteristics and the size and distribution of the species being sampled. Frequency values between 20 and 80 percent are considered necessary to both describe the plant's occurrence and detect change over time. Smith and others (1986) describe a nested frequency configuration to sample more than one species in a specific series of transects. If a single frame is used, it is critical that the quadrat size used to collect the initial set of frequency data be used on all subsequent data collections so frequency values are comparable. Statistical analysis cannot be conducted if quadrat sizes have been changed during the course of monitoring.

4. Weight. A measure of the mass of some aspect of an ecosystem may be defined as weight. As used in both ecological and fire literature, the term needs considerable redefining to be understood and thus useful. The term biomass refers to the total weight of living plants and animals above and below ground in a given area at a given time. Because total biomass is obviously beyond normal capabilities to measure, aboveground plant biomass becomes a standard reference in describing a weight aspect of plant communities. It is the total amount of living plants above the ground in a given area at a given time. A virtually synonymous term, standing crop, may be used as both a time and weight indicator of biomass, and refers to the total amount of living plant material in aboveground parts per unit of space at a given time, with particular emphasis on the specified date. Vegetation samplers often seek to measure peak standing crop, that being the maximum amount of living tissue when accumulation is greatest. Aboveground phytomass, which includes dead attached parts, is a standard expression for all organic plant parts in a specified area.

Aboveground phytomass data are useful for fire managers particularly for writing prescriptions and understanding fire behavior. The fuel load, or aboveground phytomass, carries the fire; knowing the precise fuel load prior to burning not only contributes to designing a successful fire, but permits evaluation of observed fire behavior and results of the prescription. In addition, an objective of many prescribed burns is to increase the yield of specific species, or groups of species such as grasses, on a site. Weight data must be collected in order to evaluate success in meeting the objective.

Methods employed to sample weight include clipping of quadrats, estimates, double sampling, use of height-weight curves, and use of capacitance meters. Dense, uniform vegetation requires fewer quadrats for clipping studies. The vegetation is clipped to a specific height in a specified size quadrat, air or oven-dried, and weighed. For total aboveground plant phytomass, everything but unattached litter is clipped. Litter also may be added if total fuel loading is desired. For aboveground plant biomass, also referred to as current year's production or current annual growth, all dead material must be removed from the material clipped. Weights may be estimated in the quadrats, or a double sampling scheme may be employed whereby some plots are clipped and some are estimated, and the actual weights from the clipped plots used to adjust estimated weights in the nonclipped plots. For shrubs, regressions of crown volume, stem lengths, or stem diameters have been used to estimate current annual production. Height-weight curves have been developed by researchers, particularly for individual grass species, based on the relationship of plant height to weight in the various segmented portions. Capacitance meters, which require recalibration for each site and sampling date, rest over vegetation to be sampled and, using the difference between the dielectric constant of herbage and air, estimate weight of underlying vegetation.

Actual clipping or sampling yields good information that can provide more than weight data alone. Fuel moisture content can be calculated; species can be sampled individually or lumped into categories; and botanical composition by weight can be obtained. The attribute is useful not only in determining changes in productivity on an area, but may provide information on kinds and amounts of wild and domestic animal use that may be expected in a given area.

5. Species Composition. Species composition is a term relating the relative abundance of one plant species to another using a common measurement. It is defined as the proportion (percentage) of various species in relation to the total on a given area. It may indicate the relative importance or influence of one species to another in a specific physical setting and is a reflection of structure and hence wildlife habitat. Composition can be determined by weight, cover, number, or other basic variables, and should be reported as such, e.g., percent composition by weight. Generally, it is an attribute arrived at indirectly. The attribute sampled may have been cover, but in order to understand the relationship of species to one another, the relative percents by species are calculated based on cover measurements. In a burn situation, data may be somewhat misleading if caution is not exercised in interpretation. For instance, the entire shrub or tree component may be eliminated, resulting in a dramatic increase in the herbaceous component on a percent composition basis, although no real increase in number of plants or volume of plant material produced may have been realized.

6. Number. Number is the total population of a species or classification category in a delineated unit and is a measure of its abundance. The attribute is most valuable when dealing with small numbers or particulars. In fire situations, actual counts may be important to know for a scarce resource that may be affected by the fire. Threatened or endangered species may be counted in their entirety, or numbers of snags before and after prescribed burns may be noted. Because the attribute does not involve a sample but rather the entire population, no sampling techniques except sheer counting can be described.

7. Height. Height is the vertical measurement of vegetation from the top of the crown to ground level. In herbaceous vegetation, it may be an indirect indication of productivity.

(See 4. Weight) Changes in height and hence changes in structure are some of the most important vegetation characteristics used in determining suitability of areas for various kinds of wildlife. Methods used for measuring height include the Biltmore stick, clinometer, Abney level, and Relaskop.

8. Vigor. Vigor relates to the relative robustness of a plant in comparison to other individuals of the same species and may vary with site, climatic conditions and age. It can be a subjective assessment of the health of individual plants in similar site and growing conditions based on general observations, or it can be more completely defined with some kind of "measurement" of vigor, e.g., references to seed stalk production per plant or unit area, number of tillers produced per plant or unit area, number of leaves or stems, and so forth. Vigor also can be reflected by the size of a plant and its parts in relation to its age and the environment in which it is growing. To be a useful attribute to measure for fire effects, definition of what is to be measured must be made prior to the fire, so that the term maintains a modicum of objectivity. The phenological phase of the species under observation must be the same during each evaluation in order to accurately assess and compare vigor. No matter how carefully measurements are standardized, vigor is considered subjective and is based generally on indirect measurements which may or may not relate to the actual vigor of the plant.

9. Growth Stages and Age Classes. Growth stages are the relative ages of individuals of a species usually expressed in categories. Examples of such categories are seedlings, juvenile (young), mature, and decadent plants. Age classes define in more discrete units the ages of individuals, such as 0 to 5 years, or 6 to 20 years. Age classes may be difficult to determine in herbaceous vegetation, succulents, and any vegetation that does not produce definable growth rings. Both density and frequency measurements outlined above may be made within the parameters of growth stages or age classes, so that the observer may catalogue postburn changes in reproductive capabilities of a site or in effects of the fire on the diversity reflected in different age structures.

10. Phenology. Phenology refers to the timing of various growth and reproductive phases of vegetation. It is based on yearly growth patterns of individual species. A wide variety of phases may be described and then traced for individual species as the growing season progresses (West and Wein 1971). For example, recording the time of initiation of spring growth may be valuable to assess the effects of fire on early growth before and after burning. Other phenological phases frequently recorded include time of blooming, time of seed set, initiation of new terminal bud (signalling the end of seasonal stem or leader growth) and time of dormancy. Mechanics of tracking phenology simply involve delineating the growth phases one is most interested in and then charting them as the season progresses.

11. Injury to Trees. As described earlier in this chapter (B.1.a.), percent crown scorch and percent crown consumption can be good predictors of mortality for many tree species. These can be assessed by estimating or measuring (as with an Abney level) the total length of the tree crown and the length of crown scorched or consumed. Monitoring of damage to tree stems may be needed to better understand the cause of tree death. Height of stem char is measured on all sides of the tree. Depth of char might also be a useful measure of injury on thick barked trees. If bark was consumed or is sloughing off, this should also be noted.

12. Plant Mortality. The cataclysmic effects of fire frequently result in mortality of vegetation. Conversely, in many situations it is of great value to know if plant mortality has been slight following fire.

a. Tagged individuals. A quick and easy way to assess mortality is to tag individuals prior to the fire. Pieces of tin, numbered metal tags, metal stakes, and other nonflammable materials should be used adjacent to the individuals to be checked postburn. A mapped layout of the plot will permit rapid relocation following the fire. It may be necessary to monitor mortality for several years because it may take that long for injured plants to die. Mortality of aboveground portions of shrubs, grasses, forbs, and some species of trees can be visually determined. For many nonsprouting species, death of the main stem, such as of a big sagebrush, is readily apparent, and indicates that the entire plant is dead.

Some species on the burned area are capable of producing vegetative regrowth from buried plant parts. A plant that appears to be dead immediately after the fire may sprout the following growing season. In some cases, new growth must be excavated to determine if a plant has vegetatively reproduced or if seedlings have established.

b. Chemical tests. Chemical tests can be performed to assess the death or survival of individuals of important species.

(1) Tetrazolium. Tetrazolium tests were developed to determine the degree of seed viability, but have been a standard mortality test for range situations. This chemical tests for hydrogen (dehydrogenase) that is released by plant tissues during respiration. Strong, healthy tissues develop a red stain; dead tissues remain their original color. Detailed procedure for testing grass tissue and grass seeds are given in Stanton (1975). The basic procedure is to soak the tissue of interest in a one percent tetrazolium solution, and place it in the dark. Results show up in 5 to 6 hours or overnight. Although this test has long been used, there are associated problems. Procedures for seeds vary by species, and are best performed by experienced analysts. Any sample being tested must be put in a closed container in the dark, because bright sun can affect tetrazolium and cause the same color change as occurs in the presence of dehydrogenase. Results take several hours to appear. On dark tissue, such as Idaho fescue meristems, the color change may not be visible. The interpretation of results can be a problem, because red stain may indicate something other than active metabolism.

(2) Orthotolodiene-peroxide. The chemicals orthotolodiene and peroxide are used sequentially to test for the enzyme peroxidase, found in most living plant cells. This test has been successfully used on trees, and should work well on shrubs. While no documentation of its use on grasses has been found, peroxidase should be present. However, it is not known if peroxidase is present in sufficient quantities in dormant or quiescent grass tissues to stain blue. The basic procedure is described in Ryan (1983). For trees and shrubs, a piece of cambium is extracted with an increment borer (the preferred approach), or exposed by scraping away the bark. An eyedropper is used to cover the sample with a one percent orthotolodiene solution, and then peroxide is applied. Live tissue will turn bright blue within a few moments. A reddish purple color, followed by the appearance of a blue color, also indicates life. A greenish blue color probably means dead tissue. After using this technique for a while, the colors that indicate dead or live cambium become readily recognizable. This test is preferable to the tetrazolium test because it can be used in the field and provides almost immediate results. However, caution is necessary because orthotolodiene has been found to be carcinogenic in laboratory studies. Gloves should be worn as a precaution.

(3) General comments. Metabolic by-products being tested for may not break down until a few days after a fire, even though the plant is dead. The proper location on the plant must be tested to determine mortality. On coniferous trees with living foliage, the cambium should be checked, and also the roots, if much heating occurred at the base of the tree. Trees and shrubs sprout from different locations on stems, root crowns, and roots, and it is these sprouting sites which should be tested to indicate whether the shrub may sprout. Grass crowns should be tested where the buds and reproductive meristems are found.

More than one test may be necessary per plant, because plants can survive some amount of fire damage. Tree cambium requires a test on all sides, and a shrub at several sprouting sites. Unburned meristems and buds of bunchgrasses should be tested at both the center and edges of each plant, and at different depths below the surface if the buds occur below the ground surface.

13. Burn Severity. Burn severity (discussed in II B.6.e), while not an attribute of vegetation, is an exceptionally good predictor of fire effects on vegetation. It indirectly measures the heat pulse below the surface, and provides an indicator of fire impacts on buried plant parts. Burn severity classes can be developed that apply to the type of vegetation and soil organic layer characteristics on the site being investigated. The degree of burn severity can be assigned to one of five classes, including "unburned", "scorched", and "light", "moderate", and "high" severity. Definitions for the latter three classes can be based upon the information in section B.2.c. in this chapter. Burn severity can be described as a percentage of area on plots of a specific size, or related to specific inventory points. Although a qualitative measure, this descriptor can be related to plant mortality, and amount and mode of reproduction, such as by rhizome sprouting or seed germination.

Burn severity classes have been developed for bunchgrass plants. (See VI.B.2.d.(4)) Monitoring the relationship of these classes to postfire mortality or production of specific species can provide a valuable tool for predicting postfire grass response when considering emergency fire rehabilitation, or developing prescriptions for prescribed fire use.

14. Moisture Conditions. The heat regime of a fire depends on the amount and condition of the fuel on the site, how it burns, and the duration of burning. In order to build a database that can be used to predict plant response to fire, moisture conditions at the time of a fire must be documented, because moisture levels are a key regulator of heat release during a fire. See Chapter III.B. and III.D. for a more complete discussion of fuel moisture content and how it is measured.

15. Postfire Weather. Vegetation response to fire can be dramatically affected by postfire weather, particularly in regions with arid or semiarid climates. Knowledge of postfire weather, especially precipitation, can often explain much of the measured or observed variation in postfire effects.

E. Summary

Plant response to fire is a result of the interaction of the behavior and characteristics of a fire with the characteristics of a plant. Plant community response is a product of the responses of all plants on a burned area. The response of an individual species of plant, or plant community, can vary among fires or within different areas of one fire. This is because of variation in fuels, fuel moisture conditions, topography, windspeed, and structure of the plant community itself, causing the heat regime of a fire to vary significantly in time and space. The immediate effects of fire can be modified by postfire weather and animal use. Fire can cause dramatic and immediate changes in vegetation, eliminating some species or causing others to appear where they were not present before the fire. Monitoring techniques that are used to detect trend in vegetative communities are often not appropriate, either because they are not sensitive enough to detect the changes that have occurred, or provide statistically inadequate samples. Fire effects on plants, and plant response to fire treatments are predictable if the principles and processes governing plant response are understood. If burning conditions, the fire treatment, and vegetation response are properly monitored, the fire effects that are observed can be interpreted, and our ability to predict fire effects on plants will increase.

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CHAPTER VII - TERRESTRIAL WILDLIFE AND HABITAT

By Loren Anderson

A. Introduction

Fire effects on terrestrial wildlife and their habitat are addressed in this chapter. Too many variables are involved with fire, wildlife and wildlife habitat to allow a "cookbook" approach. The underlying ecological relationships of vegetation and wildlife are briefly described. A discussion on how fire may subsequently influence those relationships through effects on food, cover, water, and space follows. Considerations for managing and monitoring fire effects on wildlife habitat are also offered.

There is an increasing literature base available regarding fire-wildlife relationships. Four publications the reader may find of particular interest are: Effects of Fire on Birds and Mammals (Bendell 1974); Effects of Fire on Fauna (Lyon et al. 1978); Fire: Its Effects on Plant Succession and Wildlife in the Southwest (Wagle 1981) and Fire in North American Wetland Ecosystems and Fire-Wildlife Relations: an Annotated Bibliography (Kirby et al. 1988). This last document includes an extensive bibliography of all literature on fire-wildlife relations indexed in Wildlife Review 1935 to 1987.

The subject of wildlife, habitat and fire is burdened with generalizations and ambiguities. The definition of wildlife varies from a taxon of invertebrates to an entomologist, a Life Form (Thomas 1979) or Guild (Short 1982) to an ecologist, or a full curl bighorn ram *(Ovis canadensis)* to a hunter. Evaluation of the quality of habitat varies depending on the perspective. Fire is frequently given the anthropomorphic rating of "good" only because fire is considered a natural phenomenon. There is a segment of the public which confuses the fact of fire with the effect of fire and envisions only death, destruction, and loss. Cool burn, hot burn, spring burn, and fall burn are terms that have definitive meaning only to the person using them. Generalizations regarding fire effects on vegetation also can be misleading. Species such as bitterbrush *(Purshia tridentata)* are frequently credited with being so severely harmed by fire that they should be given complete protection. Ultimately, however, many of them are dependent on fire or some similar disturbance (Bunting et al. 1984). Diversity and mosaic are two other commonly used terms that frequently generalize to the point of being meaningless. The widely held assumption that increased edge is always beneficial is not uniformly accurate (Reese and Ratti 1988). As there are no averages in nature (Vogl 1978), there are no generalizations that can stand alone. Terms must be clearly defined and qualified appropriately.

Oversimplification of fire effects commonly occurs when data, knowledge, time or initiative are lacking. Conversely, there is the attitude that if it is not complicated and difficult to understand, it is invalid (Szaro 1986, Vogl 1978). Providing for (as with prescribed fire) and assessing fire impacts on wildlife habitat consistent with general ecological concepts can assist in addressing many complex relationships in a more simplified manner while still retaining a level of validity (Vogl 1978).

B. Principles and Processes of Fire Effects

Adhering to ecological principles and processes is recognized as essential in preserving functional systems (Dubos 1972, Wilson 1985). More accurate effect prediction and assessment, increased assurance of success with prescribed fire, overall cost, and production efficiency are a few of the other benefits derived from thinking and acting as "ecologically" as current knowledge allows (Allen 1987, Chase 1988, Graul and Miller 1984, Savory 1988, Yoakum 1979).

Implicit is the caveat to keep all the pieces (Allen 1987, Chase 1988, Lyon and Marzluff 1984). What we may initially deem insignificant (e.g., mycorrhizal fungi) could be of ultimate importance in maintaining the stability of the ecosystem (Watt 1972, Wilson 1985). How important may lichens *(Rhizoplaca spp.)* be to the nutritional health of species such as the pronghorn *(Antilocapra americana)*? What does the insidious loss of forb diversity and abundance portend? Our imperfect knowledge of ecosystem dynamics and the ramifications of our actions make it imperative we retain the pieces and therefore, in many cases, options. Disruption and loss of indigenous ecosystems have occurred over extensive areas of the west through a combination of inadequate management, fire, and highly competitive exotics such as cheatgrass brome *(Bromus tectorum)* (Wright and Bailey 1982).

1. Floral Response.

a. Ecological basis. Much of the literature regarding fire effects, wildlife and wildlife habitat revolves around successional theory, thus, it is important to understand the concept. Floral succession - that somewhat orderly progression of occupancy by successively higher ecological order plant communities - is one of the primary descriptors of the natural environment. The progression, however, from a "pioneer" stage through various seral stages to that mostly esoteric end point called "climax," is more easily addressed in theory than fact. Although the successional trajectory is often portrayed as following a predictable path and timeframe, there are many who question that view (Bendell 1974, Dubos 1972, Leopold and Darling 1953, MacMahon 1980, Watt 1972). The observation that some species such as gambel oak *(Quercus gambelii)* are successional in one environment and climax in another further complicates the picture (Harper et al. 1985, Whittaker 1975). The "orderliness" of succession we like to envision is commonly disrupted and altered by stochastic events we can neither anticipate nor control (Rosentreter 1989). The apparent controversy does not invalidate successional theory, but it does point out the limitations of our knowledge and the need for being inquisitive and prudent.

b. Structural development. Habitat structure follows successional trends in most plant communities. Short fire intervals tend to maintain or promote early successional conditions typified primarily by herbaceous species and comparatively limited structural diversity. Long fire intervals favor community development along the successional trajectory. This normally results in increased woody species development and greater horizontal and/or vertical structural diversity.

c. Postburn plant community.

(1) For the most part, preburn plant composition and the individual plant species response to fire determine membership of the initial postburn floral community. Understanding plant survival mechanisms (see VI.B., this Guide) is essential for assessing wildfire effects on habitat and in providing for desired prescribed fire effects.

(2) Plants stressed through drought, disease, insect infestations, overgrazing, old age or a combination of these factors are likely to be negatively impacted by burning regardless of how they would respond if healthy (Bunting 1984, DeByle 1988b, Wright and Britton 1982). However, trees that die as a result of fire can provide an important habitat component for certain species.

(3) Herbaceous production increases occur most often on range sites in high Fair or better ecological condition (Bunting 1984, West and Hassan 1985).

(4) Various animal species disseminate seed and can influence subsequent floristic makeup of an area. Pinyon jays *(Gymnorhinus cynanocephalus)* have been credited with the ability to transport upwards of 30,000 pinyon *(Pinus spp.)* seeds per day up to 6 miles (9.7 kilometers). Both birds and small mammals are considered instrumental in the expansion of pinyon-juniper woodland (Evans 1988). Small mammals, such as chipmunks *(Tamias spp.)*, disperse spores of mycorrhizal fungi into burned areas, an essential component for the establishment and survival of many plant species. (See V.B.c.(4).)

(5) Increases in plant nutrient density, palatability and earlier "greenup" are not unusual occurrences (Bendell 1974, Daubenmire 1968a, Leege and Hickey 1971, Wagle and Kitchen 1972). Earlier greenup of burned areas is largely a function of heat absorption by the dark ash and resultant increases in soil temperature. Reduced soil shading is also a factor. Plants surviving a fire take advantage of higher nitrogen levels provided by the ash and remain greener, more nutritious and more palatable for a longer period of time (Brown 1989). However, this phenomenon is normally shortlived. Commonly, available nitrogen returns to normal levels within two to three growing seasons. Personal observation (Anderson 1983) indicated elevated crude protein levels for 7 years following burning on a bighorn sheep winter/spring range. The extended period of increased protein levels was believed due to subsequent utilization made by bighorns rather than from burning, however.

2. Faunal Response.

a. Ecological basis. Faunal succession follows floral succession, i.e., a given set of vegetational conditions provides habitat for a more or less distinct collection of wildlife species (Bendell 1974, Burger 1979, Dasmann 1978, Evans 1988, Huff et al. 1984, Smith et al. 1984, Wolf and Chapman 1987). Maser et al. (1984), however, pointed out that ecological distinctions between plant communities do not uniformly correlate with differences in animal communities. That apparent inconsistency is explained by the observation that wildlife species most often select habitat on the basis of structure rather than plant species composition. Thus, most of the literature discusses faunal response in terms of general vegetational structure and successional stage.

Fires which set succession back to a grass/forb stage primarily benefit herbivores (vertebrates and invertebrates) and those species for which herbaceous vegetation is desirable for cover. Various vertebrate and invertebrate predators of herbivores also may benefit (Beck and Vogl 1972, Bendell 1974, Hansen 1986, Huff et al. 1984, Lyon and Marzluff 1984, Lyon et al. 1978, McGee 1982). Red foxes *(Vulpes fulva)*, gray foxes *(Urocyon cinereoargenteus)*, and weasels *(Mustela spp.)* are associated with early to mid-successional stages and the ecotones between these stages and climax vegetation communities (Allen 1987). Whitetail deer *(Odocoileus virginianus)*, bobwhite quail *(Colinus virginianus)* and cottontails *(Sylvilagus spp.)* are common to early-mid stages (Dasmann 1978). Fagen (1988) notes a dependency on old growth timber, especially during years of heavy snowfall, by Sitka black-tailed deer *(Odocoileus hemionus sitkensis)*. Muskrats *(Ondatra zibethicus)* are favored by early successional conditions (Allen 1987). The spotted owl *(Strix occidentalis)* is primarily an inhabitant of old growth forests (USDI-Fish and Wildlife Service 1989). As broad as the preceding descriptions may be, they do provide a relative perspective of floral/faunal relationships. Habitat manipulation almost invariably involves efforts to either set back, retard or accelerate plant succession (Burger 1979, Huff et al. 1984, Wolf and Chapman 1987). Most animal species are more cosmopolitan in their use of various successional stages and structural conditions for feeding than for cover, escape or reproduction (Dealy et al. 1981, Maser et al. 1984).

b. Structure.

(1) The consistency with which the value of structure is referred to in the literature (e.g., Allen 1987, Geier and Best 1980, Harris and Marion

1981, McAdoo et al. 1989, McGee 1982, Smith et al. 1984) gives credence to the assumption that structure is possibly the single most important habitat clue to which wildlife responds. Structure may indicate a feeding site for one animal. For another, that same structure may be sought as nesting cover. The perceptual environment differs from species to species and a structural "clue" for one may mean something entirely different to another species (Dubos 1972). Although specific plant species are frequently insignificant (Johnsgard and Rickard 1957, McAdoo et al. 1989), vegetational complexity associated with developing structural diversity is significant, particularly when faunal species richness is the objective (Campbell 1979, Germano and Lawhead 1986, Johnsgard and Rickard 1957, Short 1983, Willson 1974). A variety of "clues" accommodates interspecies variance and automatically denotes a variety of potential habitat niches. Addressing Great Basin habitats in southwestern Utah, Germano and Lawhead (1986) found postbreeding bird diversity significantly correlated with vertical habitat layering and that diversity of both rodents and lizards correlated with horizontal habitat heterogeneity. Birds make more efficient use of habitat volume or vertical space than other classes of wildlife. Although structure is not height limited, Hall (1985) equated herbaceous stubble of 1 to 2 inches (2.5 to 5.1 centimeters) to bare ground for many species that nest and feed on the ground.

(2) The addition of a single structural element to a plant community can greatly enhance faunal species diversity (Germano and Lawhead 1986, Willson 1974). Maser and Gashwiler (1978) reported that the presence of pinyon and juniper trees provided habitat for four additional Life Forms that would otherwise not be present. Conversely, the loss or lack of a single structural component can eliminate some species and be just as lethal as a direct mortality factor (Knopf et al. 1988, Lyon and Marzluff 1984, Wecker 1964).

(3) Habitat and community structure can include dead as well as living components. Large diameter logs provide habitat in the form of travel routes, as well as feeding, nesting, and reproduction (Bartels et al. 1985). Snags are critical nesting and feeding habitat for many species of birds, as well as mammals and amphibians (Neitro et al. 1985). Insectivorous birds that inhabit snags not only harvest insects in recently burned areas, but help regulate populations of insects in adjacent unburned areas, and in the newly developing forest (Wiens 1975 in Neitro et al. 1985).

(4) The interplay between only one or two structural components and subsequent wildlife use is illustrated in the following examples. In a sage *(Artemisia spp.)* shrubsteppe, horned larks *(Eremophila alpestris)* and meadow larks *(Sturnella neglecta)* are favored primarily by a grass stage. Sage *(Amphispiza belli)* and Brewer's sparrows *(Spizella breweri)* are favored by a shrub stage. All four species can exist in nearly a 1:1 ratio in a mixed grass/shrub type. Lark sparrows *(Chondestes grammacus)* appear to benefit more from the mixture than either the grass or shrub stage alone (McAdoo et al. 1989, Rotenberry and Wiens 1978). Rotenberry and Wiens (1978) noted that horned larks replaced sage sparrows as dominant following a burn that eliminated sagebrush. Pronghorn have a somewhat similar potential response to the lark sparrow's. They, too, are benefitted most by a combination of herbaceous and shrub components. Their habitat quality drops rapidly if either component is depauperate or, in the case of sagebrush, too tall or dense (Yoakum 1980).

(5) The Life Form (Thomas 1979, Maser et al. 1984) and Habitat Guild (Short 1982) concepts are organized around the relationship between plant succession and resultant structural conditions, and wildlife. The basic premise is that there are groups of animals with similar ecological requirements that are met by similar successional stages of the plant community. Not unlike successional theory, there are some who question aspects of that approach (Block et al. 1987, Szaro 1986). The Life Form approach to assessing and predicting effects (see Maser et al. 1984) can be of considerable value, however, when large scale fires are addressed. It is important to recognize that within a given Life Form, a full range of species adaptability and species-specific niche requirements may be encountered. The habitat needs of individual species in a given Life Form may have to be scrutinized to assure adequate consideration is given sensitive animals.

c. Species adaptability. Animals that are broadly adaptable behaviorally and in their habitat preferences can accommodate change more efficiently -- they have more options (Dubos 1972, Knopf et al. 1988, Vogl 1978, Watt 1972, Wecker 1964). These species are frequently termed generalists, species of high versatility (Maser et al. 1984) or eurytopic (Knopf 1988). Deer mice *(Peromyscus maniculatus)* and the ubiquitous coyote *(Canis latrans)* are two common generalists. At the opposite end are species that have a narrow range of environmental conditions under which they can survive and flourish. At the extreme are the species that appear on "sensitive" or threatened and endangered species lists. Species of specialized adaptability are commonly termed specialists, of low versatility (Maser et al. 1984), obligates (Kindschy 1986) of a particular habitat component, or stenotopic (Knopf et al. 1988). Hammond's flycatcher *(Empidonax hammondii)* has very narrow food and cover requirements (Maser et al. 1984). The sage grouse *(Centrocercus europhasianus)* and pinyon jay are considered obligates of sagebrush and pinyon-juniper woodland respectively (Kindschy 1986, Hardy 1945). Allen (1987) notes that many furbearers of forested and wetland cover types have specific habitat requirements and are less resilient in adapting to habitat modifications. Specialists commonly can be eliminated by loss of a single habitat component. Species of intermediate adaptability such as robins *(Turdus migratorius)* and red-wing blackbirds *(Agelaius phoeniceus)* are referred to as mesotopic (Knopf et al. 1988). Knopf et al. (1988) separated riparian avifauna into eurytopic, mesotopic, and stenotopic guilds to accommodate variations in habitat sensitivity.

d. Food and cover. The two most visually obvious determinants of habitat suitability are food and cover.

(1) Dense timber travel lanes are frequently preferred by elk *(Cervus elaphus)*. Sagebrush can reach heights and densities that inhibit or prevent pronghorn movement. Voles *(Microtus montanus; Clethrionomys gapperi)* require certain litter layer or woody debris habitat components. Birds require various structural conditions for nest sites, hunting and song perches. Some species (e.g., the white-tail deer) select for denser woody vegetation. Species such as bighorn sheep or pronghorn normally select against it (Lyon et al. 1978, McGee 1982, Yoakum 1980).

(2) One species may consume primarily grass and forbs (e. g., grasshoppers or elk), another mostly forbs and shrubs (e.g., sage grouse or pronghorn) and yet another, such as turkey *(Meleagris gallopavo)*, may make heavy use of mast. Hobbs (1989) provides a strong case that the habitat mule deer *(Odocoileus hemionus)* need for thermal cover correlates well with the nutritional plane of the animal. Hobbs and others have noted the inherent value of forage diversity and availability. Hobbs and Spowart (1984) found substantially improved winter diet quality for both deer and bighorn sheep as a result of burning although there were only relatively small changes in the quality of individual forages. They attributed the diet quality increase to improved availability of forage items and enhanced forage selection opportunities.

It is commonly assumed that increased herbaceous production automatically occurs after burning.

There is sufficient documentation, however, indicating production increases are not a foregone conclusion (Peek et al. 1979, Yeo 1981 and others). Certainly, some highly valued food items can be eliminated if burning is too frequent. For example, McCulloch et al. (1965), determined that Gambel oak produce very few acorns before reaching 2 inches dbh (diameter at breast height) (5.1 centimeters) and that maximum production of mast probably does not occur until healthy stems are 12 to 14 inches (30 to 36 cm) in diameter. Management of Gambel oak for both mast production and deer winter browse may not be possible on a given site.

(3) The differential effect fire has on wildlife is typically noted in a realignment of species as some species become favored over others as a result of changes in abundance of food and cover. For some classes of wildlife (e.g., birds and small mammals), stability of total numbers has beennoted, even though species composition changed (Lyon and Marzluff 1984, Lyon et al. 1978, McGee 1982). Bendell (1974) explained changes in the kind and frequency of parasitic infections following burning as likely a result of alteration of habitat structure and cover favored by intermediate hosts. He noted a trend towards more species of parasites in greater frequency of infection with longer time after burning. He stressed, however, that there is a broad response range and that any blanket statement regarding fire effects on parasites must be qualified.

(4) Various efforts have been made to "codify" vegetational requirements for a few species. Yoakum (1980) outlines some fairly specific vegetational conditions that constitute quality pronghorn range in shrub-grasslands. Autenrieth et al. (1982) and others have developed similar recommendations for sage grouse. Allen (1987) and Parker et al. (1983) note vegetational criteria for pine marten *(Martes americana)* and lynx *(Lynx canadensis)* respectively. A growing number of plant community/wildlife association listings are available. Most are built around the Life Form (Thomas 1979) or Habitat Guild (Short 1983) concepts that relate wildlife use to structural conditions. Maser et al. (1978) address wildlife species of the western juniper type; Maser et al. (1984), fauna of the Northern Great Basin; Allen (1987), furbearers; Harper et al. (1985), wildlife of the oak brush type, and Thomas (1979) and Brown (1985) address coniferous forest wildlife. Brown (1985) is somewhat unique in the level with which fish and amphibians are addressed.

e. Influence of time.

(1) Each wildlife species has a unique reaction to fire and the subsequent ecological changes caused by fire. Some species exhibit an almost immediate reaction. For others, behavioral time lags and site tenacity may extend the response time nearly indefinitely (Wiens et al. 1986). Eurytopic or generalist species can likely accommodate the change more efficiently than stenotopic or obligate species (Lyon et al. 1978).

(2) Immediate postburn effect assessments can be a poor reflection of long-term animal use. For example, McGee (1982) noted that mountain voles *(Microtus montanus)* could not sustain populations on severe fall burns. Repopulation was contingent on the subsequent development of an adequate herbaceous mulch layer. Red-back voles *(Clethrionomys gapperi)* require woody cover and moisture conditions (Getz 1968) that may be eliminated by fire. Four years following a fire, however, red-back voles may be the most common mammal present (Moore 1989). A decadent stand of bitterbrush under a pinyon/juniper overstory may be providing valuable deer forage. Burning that habitat may be the only hope for assuring <u>any</u> bitterbrush is available for some future generation of deer (Bunting et al. 1984). Huff et al. (1985) found that the highest diversity of birds occurred in a 19-year-old forest in the Olympic Mountains of Washington. Moore (1989) stated that burned forest 5 to 10-years-old becomes prime habitat for chipmunks, possibly even better than the original forest. He associated improved chipmunk habitat with development of complex shrub layers.

Bunting et al. (1984) observed managers must not be so concerned with the short-term effects that they lose sight of the future needs of species. A fire-damaged tree, for example, may not die for several years, but then provides important habitat for cavity nesting birds for a long time. The species that use the snag change over time as the snag decomposes. In many more years the snag falls, becoming a forest floor log that is habitat for many other species.

f. Extrinsic/intrinsic influences. Both extrinsic and intrinsic factors direct individual species response to fire effects. Extrinsic factors include such items as food, cover, water, predators, and other elements of the external environment. A noticeable population increase, decrease, or shift in use patterns would indicate burning had modified some extrinsic factor(s), creating or removing a limiting element, or creating a more desirable (not necessarily required) condition. Physiological, behavioral andgenetic characteristics are intrinsic factors that play a large role in determining how a species responds to a burned area. When no particular response occurs it may be assumed the impact of fire was inconsequential or that there were overriding intrinsic factors that inhibited or prevented a response (Bendell 1974, Moen 1979, Wolf and Chapman 1987). The presence or absence of one species can influence the presence, absence or habitat utilization pattern of another (Bendell 1974, Peek et al. 1984). Extrinsic and intrinsic factors are not mutually exclusive and the seemingly endless combinations of the two can easily make an absolute determination of fire effects virtually impossible in many cases. Peek et al. (1984) found positive results from fire on seven different bighorn sheep ranges. They indicated however, that in each case, definite proof was lacking because they were unable to isolate the effects of fire from other potential factors. Wiens et al. (1986) also noted confounding elements associated with trying to evaluate the effects of small-scale burning on shrubsteppe avifauna.

3. Burn Characteristics: Influence on Potential Faunal Response.

a. Size of burned area. A number of small burns produces more edge than a single large burn. More edge is commonly assumed to provide more benefit to more species of wildlife (Odum 1966, Thomas et al. 1979, and others). When particular species are considered, however, the picture is not that clear. A number of 5 to 10-acre (2 to 4-hectare) burns in a pinyon-juniper/ sagebrush-bunchgrass type might be relished by mule deer but be of little or no value to pronghorn. Some species, such as the western flycatcher *(Empidonax difficilis)* and brown creeper *(Certhia americana)*, are seldom found associated with edge and actually may be harmed if edge is increased at the expense of adequate forest interior (Rosenberg and Raphael 1986). The creation of fragmented habitat for some species is a potential concern, especially with large scale fires. Burned areas are a considerable attraction for many herbivores. Larger species such as elk, moose *(Alces alces)*, bighorn sheep, domestic cattle *(Bos taurus)*, and wild horses *(Equus caballus)* are capable of overutilizing burns of insufficient size to accommodate their demand.

b. Burned area configuration.

(1) Patchy or irregular burns can enhance habitat diversity, particularly in an area with only one or a few communities all in the same structural condition. Increased diversity and resultant increases in edge effect makes more niches available for partitioning. Edge length, width, configuration, contrast, and stand size largely determine the degree of benefits. It must be recognized that diversity and edge cannot be increased indefinitely. Beyond some threshold, the pieces become sufficiently small and mixed that they assume a sameness or homogeneity (Thomas et al. 1979). Also, increased fragmentation of habitat components caused by maximizing edge can eliminate those species requiring larger tracts or that inhabit stand interiors (Reese and Ratti 1988). The amount and type of diversity sought with prescribed fire is determined by the management goals and objectives. Maximum diversity provides for species richness but is incompatible with an objective to maximize a particular species. The reader is referred to "Edges" by Thomas et al. (1979) for one of the more concise and understandable treatments of diversity and edge. "Edge Effect: a Concept Under Scrutiny" (Reese and Ratti 1988) is a good companion treatise offering qualifying considerations of the edge concept.

(2) Areal extent, composition, and orientation of habitat components (food, cover, water, space) determines habitat suitability for individual species and/or groups of species. Juxtaposition, interspersion, complexity, diversity, and mosaic are terms commonly used to reflect the physical mix and patterning of edges, structural components, plant communities, and seral stages. These somewhat generic terms give a relative idea of the variety and positioning of resources within a given area. Nearly mystical qualities have been attached to these terms and they are frequently (and improperly) used without qualification. The ideal mosaic for a soil-surface invertebrate obviously sayslittle about the optimum mosaic for sage grouse. A sage grouse habitat mosaic has no relationship to a mosaic promoting coniferous forest avifauna species richness. A "good" mosaic is meaningful only within the context of a specific management goal or objective (Thomas et al. 1979).

(3) The scale of the postburn configuration or mosaic is a major consideration. Whether the components (structure, cover, openings) are measured in square inches, acres or miles can dictate which species benefit. Thomas et al. (1979) suggest that wildlife species richness should be approaching maximum in rangeland settings where "average" habitat size is approximately 200 acres (81 hectares). It is recognized that habitat requirements of individual species determine the relative potential benefit of a particular size burn where species richness is not the primary objective.

A seldom discussed aspect of habitat quality is that of habitat fragmentation (Reese and Ratti 1988, Rosentreter 1989). Small isolated islands of shrubs and trees following prescribed or wildfire are examples of fragmented habitat. Many wildlife species exhibit high extinction rates in fragmented habitat (Wilcox 1980). Fragmented habitat fails to provide areal extent and linkages between and among components that are implied with "quality" mosaic, juxtaposition, interspersion and diversity for a given species or collection of species. Adequate linkage of habitat components (e.g., a stringer of cover connecting larger areas of escape cover) is a determining factor for many species. As with other wildlife/habitat considerations, some species are favored over others by a particular mosaic or juxtaposition of elements and a few species may be eliminated entirely.

c. Burned area location. The location of a burn relative to animal use patterns can have a major influence on subsequent use. The proximity of propagules or potential inhabitants has an influence on what species may occur on a burn site. Species mobility also plays a part. A young bighorn ram may travel miles, a shrew *(Sorex spp.)*, hardly any. Whether potential inhabitants can see, smell or be expected to wander across a burned area may dictate the presence or absence of a particular species. An otherwise "excellent" burn (prescribed or wild) that is too distant from traditional use areas (e.g., bighorn) may not be utilized in any reasonable timeframe. Proximity of the burn to a critical habitat component such as water or cover also determines use. Sage grouse exhibit a reluctance to use water sources devoid of adequate surrounding cover. In contrast, pronghorn generally avoid water sources screened with tall dense vegetation. Loss of a critical habitat component and how soon - if ever - that element is replaced may be of paramount importance. Burn location can strongly influence ultimate vegetational establishment. A small stand of Douglas-fir *(Pseudotsuga menziesii)* on a steep south exposure may - from a practical standpoint - never regenerate whereas a similar stand on a more moist north exposure may be restocked in comparatively few years. Slope, aspect, and elevation affect snow deposition, snow crusting, thermal patterns, and wind conditions on burned areas. All of these factors have a bearing on habitat quality for a given species.

d. Completeness of burn. A fire of low burn severity and low fireline intensity, which consumes comparatively little of the existing plant community, may have no perceptible impact on wildlife. However, the high severity, high intensity fire can significantly alter habitat makeup, sometimes for an extended period of time. The first example may have influenced plant community succession very little. The second could result in a major adjustment of seral position potentially resulting in significant changes in structure, cover and the forage base. It is common to see both examples and many variations of the two on a single fire.

e. Timing of burn. Timing of a fire relative to plant phenology is a primary factor dictating the postburn plant community makeup. Perennial herbaceous species, for example, are most resistant if burned when completely dormant (Britton 1984, Bunting 1984). The size and phenological stage of coniferous tree buds influences their resistance to fire. Large buds such as on ponderosa pine *(Pinus ponderosa)* that have scaled out are more resistant than small and/or scaleless buds (Ryan 1988). (SeeVI.B.1.a., this Guide.) Negative impacts may occur if a vital habitat element for a species is burned at the "wrong" time. For example, a fall burn that consumes bighorn sheep winter range could be disastrous, at least in the short term. If that fire occurred early enough in the spring for regrowth, it may be beneficial (Peek et al. 1984). The effect of fire on birds nesting in residual herbaceous vegetation can vary markedly depending on whether the fire occurred before, during, or after nesting activities were completed.

4. Direct Mortality. Fire related mortality is popularly considered insignificant and generally ignored. That generalization can be very misleading - at least on a site specific basis. There is no reason to believe various wildlife species have some superior capability to predict fire behavior or to locate safety zones through dense superheated smoke. Animals do die, apparently, most often through suffocation (Lawrence 1966). At times, the number may be high. Quinn (1979) reported that an intense burn eliminated all small mammal species but the kangaroo rat *(Dipodomys heermanni)*. Nelson (1973, p. 139) relates a very graphic eyewitness account of large numbers of dead and dying buffalo *(Bison bison)* that were caught in a prairie fire in the early 1800's. There are indications that severe burning can cause potentially long-term reductions in some insects and other invertebrates of the soil surface layer (Lyon et al. 1978). A long-term loss of these invertebrates could be of particular significance in the altered and frequently truncated ecosystems affected by man. Highly mobile species and species that can escape underground or into rock crevices are least subject to direct mortality (Beck and Vogl 1972, Lawrence 1966, McGee 1982, Starkey 1985). Direct mortality is unlikely to have much effect on many species if the entire population or range of those species are considered. In a particular geographic setting, however, the potential significance of that loss should at least be considered.

5. Miscellaneous Considerations.

a. Noxious weeds and exotic plant species. Noxious weeds and exotic plant species are an increasing concern. Any wild or prescribed fire occurring or planned in areas subject to noxious plant invasion should be evaluated from that standpoint.

b. Human effects on subsequent use. Fences, roads, human activity and other similar factors, either on or off-site, can significantly influence subsequent wildlife use.

c. Livestock use. Burns are an attraction to many animals and livestock are no exception. Fires occurring on slopes less than about 35 to 40 percent may be subjected to heavy use by all classes of livestock. Horses may make excessive use of burns regardless of location. Livestock can easily influence potential wildlife values of a burned area by altering plan responses, reducing herbaceous habitat structure, removing forage, and merely by their presence. Control and management of livestock is essential.

d. Snow crusting. Wind crusting of snow is a common problem on some deer winter ranges. Carpenter (1976) documented that a sagebrush canopy disrupts wind crusting in addition to providing frequently melted out areas around larger plants. Sagebrush stands approaching 20 inches (51 centimeters) in height have been found to collect up to 1 inch (2.5 centimeters) more water in the form of snow than open grassland (Hutchison 1965). Haupt (1979) noted that small burns in climax coniferous forests accumulate more snow than unburned forest. He found a similar result on larger burns if there was residual tree cover. However, if burn size exceeded four times the height of surrounding tree cover, snow accumulation could be reduced through wind scour.

e. Indirect effects. The possibility of remote or very indirect wildlife-fire effect relationships should be considered. For example, there is little question the current concern and management efforts directed toward aspen *(Populus tremuloides)* stand rejuvenation are valid. Robb (1987) however, found that 85 to 90 percent of all gastropods infected with bighorn sheep lungworm *(Protostrongylus spp.)* larvae in her study area, resided in aspen stands and aspen edges. Could fire in an aspen type in one area have potential implications for bighorn monitored in another? As difficult as it may be, effort must be extended to look at the whole system; to think and act within an ecological perspective (Savory 1988).

f. Stochastic events. Climatic and weather related events such as drought, abnormally high precipitation, shifts in precipitation regimen, and unusually hot or cold temperatures can have a marked effect on the interpretation of fire effects. Large populations of insects such as the Mormon cricket *(Anabrus simplex)* can consume remarkable amounts of vegetation in a relatively short time thus clouding fire effects evaluations.

C. Resource Management Considerations

Understanding existing management goals and objectives for an area is essential. It is recognized that site specific objectives may not be in place to adequately address every wildfire situation. Some objectives may even be mutually exclusive. It is recommended that a familiarity with fire terminology be developed to facilitate communication on wildfires and in planning for prescribed fire. The Fire Effects Information System (F.E.I.S.) contains a wealth of information and is an invaluable aid in predicting and assessing fire effects. (See XII.D.4., this Guide.)

Every fire is a "wildlife" burn. Only through careful consideration, accommodation and management of factors influencing the results of fire can wildlife goals and objectives hope to be met.

1. Define Terrestrial Wildlife Habitat Goals and Objectives.

2. Standard Considerations for Fire Suppression.

a. Protection of habitat improvement projects. Protect habitat improvement projects such as guzzlers, nest structures, browse plantations, fences, and recent prescribed burns.

b. Water. Water quality and flow considerations are of vital importance to many species of wildlife. Efforts to protect water include, but are not limited to, the following:

(1) Prohibiting the washing or rinsing of any container or equipment containing potentially harmful substances in or near any spring, stream, pond or lake. Containers would include such items as helicopter buckets, retardant tanks, engine tanks, backpack pumps, and other such items. Potentially harmful substances include, but are not limited to, wet water, foaming agents, and petrochemicals in any form.

(2) Avoid the dropping or spraying of retardant, wet water, or foaming agents directly on, or immediate to, wetlands, springs, streams, ponds or lakes.

(3) Avoid alteration or damming of stream courses.

c. Control of vehicle and heavy equipment use.

(1) Restrict travel to existing roads to the extent possible.

(2) Avoid any travel in or across streams or wet meadows, or through unique or limited habitats.

(3) Physically close and rehabilitate all firelines that potentially offer ORV access.

d. Control of aircraft use.

(1) Establish low-level flight routes that avoid important habitat areas such as bighorn sheep summer range, raptor nest sites, and waterfowl nesting areas.

(2) Avoid harassment of big game or other species of wildlife.

e. Wildlife barrier management.

(1) Bulldozer-line windrows through timber or heavy brush should be broken up, lopped and scattered. At a minimum, they should be breached at all drainage crossings and at intervals between drainages to facilitate movement of big game.

(2) Where trees have been slashed around ponds or other bodies of water used to facilitate bucket drops, the slash should be reduced to a depth of no more than 18 inches (46 centimeters) and/or travel lanes cut through for wildlife access to the water.

3. Species Habitat Requirements.

a. Structure. Species structural requirements for feeding, hiding cover, reproductive cover, thermal cover and ease of movement should be a primary consideration. It is important to keep in mind that structure per se is not defined by height (i.e., a short-grass meadow is just as much a structural component as an impressive stand of grand fir). A number of species-specific habitat management guides are available which address structural requirements. Life Form, Habitat Guild, and other similar listings also can be of assistance.

(1) How do current structural conditions compare with the perceived optimum for a featured species or management for species richness? The areal extent, shape, height, age, density, and orientation of structural components, and the necessary linkages between and among those components should be addressed. If structural conditions of vegetation are at or near the perceived optimum and in a healthy condition, fire would not be of benefit. It is important to remember the value of nonliving structural components such as snags and downed logs. Fire may have a positive effect on these features, such as when fire creates snags, or a negative effect when a severe fire consumes most downed woody debris.

(2) How adequate are structural conditions adjacent to the proposed burn or wildfire? A number of species (e.g., elk, mule deer, and others) more readily use burned areas if their cover requirements are met in close proximity to the burned area. In some vegetation types (e.g., sagebrush-grass), the "best" habitat frequently burns because it has the highest fine fuel loading.

(3) What structural conditions and orientation are desired within the fire area? For example, some species may require certain cover characteristics along drainage courses, from drainage courses to ridge lines and/or along ridgelines to make efficient use of burned areas.

(4) What postburn timelags for structural development are tolerable? If no timelag is acceptable, that structural condition should be afforded protection from fire. Threatened or Endangered species, species classed as "sensitive," and species that are obligates of late seral conditions are species likely intolerant of any habitat loss duration if that loss is of sufficient size. The opportunity for accepting short-term structural losses for long-term gain should be explored, however.

Factors influencing plant response time include:

(a) Plant survival mechanism;

(b) Plant health;

(c) Phenological stage;

(d) Preburn and postburn management;

(e) Stochastic events such as drought, torrential rains, insect or disease outbreaks and other unpredictable and largely uncontrollable occurrences.

b. Behavior. Behavioral attributes may influence species response. Nominal home range size, territory, interspecific compatibility, sensitivity to human disturbance, site fidelity, preference for open vistas (e.g., antelope, bighorn sheep), preference for denser cover (e.g., white-tail deer, ruffed grouse), and other aspects of behavior can have a profound effect.

c. Food habits. Food habits must be considered. An animal that depends on a comparatively few select food items is more sensitive to fire effects than a species with more cosmopolitan dietary requirements. The following is oriented toward herbivorous species with the understanding that predators and scavengers are indirectly affected through their prey base.

(1) What shift in available food items may occur as a result of burning? Fire of sufficient fireline intensity and/or burn severity could benefit grazers at the expense of browsers. Browsers could benefit from a fire in a habitat type such as oak brush but species dependent on mast produced by that oakbrush may be negatively impacted for many years.

(2) Will food items be available when the species requires them? For example, a fall burn could eliminate critically needed forage for wintering herbivores. A fire on that same site early enough in the spring to promote substantial regrowth, could be beneficial.

(3) Is fire-sensitive vegetation involved in the food base? Long-term negative impacts can be incurred if an animal is dependent on a fire-sensitive species that burns. The opportunity, however, for accepting short-term forage loss for long-term enhancement of the food base should be considered.

d. Water availability. Free water availability dictates the presence or absence of many species following a fire.

(1) Is water present on or close to the burned area? Some species will travel miles for water. Others, however, need it immediately available.

(2) Is the water present yearlong or on a seasonal basis?

(3) What cover characteristics are present immediate to the water? Some species (e.g., sage grouse, white-tail deer) show a reluctance to use a water source deficient of adjacent cover. Other species, such as antelope, prefer good visibility.

(4) The potential adverse effects of fire on water quality -- both onsite and off-site -- should be addressed. Water quality can have a major influence on food chain relationships.

4. Miscellaneous Considerations.

a. Size of burned area. Is the burn of sufficient size to accommodate the forage demand of large herbivores? Deer, elk, bighorn sheep, livestock, and a number of other species are capable of making excessive use of burned areas that are of insufficient size. Many of these species exhibit a strong affinity for burned areas. Options to consider include:

(1) Burn additional similar size areas;

(2) Increase the size of the prescribed fire unit;

(3) Protect burned areas with fencing or by herding (as with domestic sheep);

(4) Reduce numbers of animals generating the demand;

(5) Unless otherwise accommodated by management, conduct prescribed burns for wildlife on cattle allotments on areas not readily accessible to livestock, such as steep slopes.

b. Noxious weeds and exotic plants. Potential for noxious weed and/or exotic plant invasion should be addressed and management adjusted as necessary.

c. Potential changes in human access. Is the burned area in or near zones of human activity? Human activity associated with roads, campgrounds, ORV use, and other sources can strongly influence the presence, absence or habitat use efficiency of many species. Bulldozed firelines may create undesirable access. Burned areas may attract recreational use by snowmachiners, skiers and others. Closures to protect wildlife may be necessary.

d. Snow. Will the habitat quality of some species be altered by changes in snow deposition and crusting factors as a result of burning?

e. Snags.

(1) Adequate snag protection should be incorporated into prescribed fire plans. The opportunity to protect snags under certain wildfire situations may also be present. Damage to snags from fire can be limited by such measures as hand pulling or machine piling fuel away from their base, and applying fire retardant foams around the bottom and along the bottom part of important snags. Leave some living trees with broken tops that will eventually become snags, and provide raptor nesting habitat in the interim.

(2) When conducting postfire salvage logging, leave some dead or dying trees to become future wildlife trees.

f. Downed logs. When prescribed burning, ensure that a certain number of logs of a minimum specified diameter are left onsite. If broadcast burning, prescribe moisture contents high enough in the larger diameter material that it does not burn. If pile burning, leave logs out of the piles.

D. Methods to Monitor Fire Effects

This section views some considerations for monitoring fire effects rather than specific techniques.

1. Animal Population Changes. It is suggested that monitoring of animal population changes be avoided unless there are overriding reasons to do so. As noted previously, intrinsic factors and synergistic relationships between and among plants and animals can easily confound cause/effect assessment of fire effects on populations. The sophistication of study design and execution, time and cost of such studies is normally beyond field office capabilities. Contract studies or support of cooperating agencies, organizations or institutions should be investigated when such information is required.

2. Objectives.

a. Well-defined and measurable. Well-defined, measurable objectives that describe essential plant community characteristics greatly facilitate monitoring. For example, an objective to increase herbaceous production for elk forage would require much more monitoring effort if it were written to increase specific plant species rather than the total production of herbaceous plants elk utilize. Yoakum (1980) indicates a variety of forbs is required on quality pronghorn range. Specific forbs are apparently of little importance. An objective to increase the variety of forbs is much simpler to monitor than one that requires the absolute determination of plant species. The same consideration holds for objectives relating to structure.

b. Expressed in absolute terms. Objectives expressed as percent composition are essentially meaningless unless accompanied by an element addressing ground cover, pounds production, or some other absolute. For example, 50 percent grass and 50 percent sagebrush on a rangeland could mean anything from one grass plant and one sagebrush plant to 500 pounds (227 kilograms) production of grass and 500 pounds of sagebrush.

3. Monitoring Level. The level of monitoring required needs to be defined. There is a temptation to set up monitoring procedures of detail or sophistication that are unwarranted for management purposes. Monitoring procedures should match the issue sensitivity. For example, if only an index of bighorn sheep preference for a burned area is needed, a simple grazed-ungrazed plant transect inside and outside of the burn may suffice. An effort that addressed factors such as comparative production by plant species, chemical analysis of forage, and pounds of various plant species utilized by bighorns inside and outside the burn would be "overkill." The latter approach might be appropriate, however, if bighorn sheep use of a burn was a controversial issue or some detailed information regarding their ecology was needed.

4. Consistency of Technique. Maintaining consistency of technique is essential. The plot that is estimated one year, measured the next, and perhaps photographed the next, does not allow for any meaningful comparisons among years.

5. Observations. The value of observational information should not be overlooked. Frequently, this subjective information provides the critical links with more formal data to clarify what actually transpired due to fire or whether the apparent effects were due to another reason. Anyone who has had an occasion to be on the site, either during or following the fire, is a potential source of information. Observations should be properly documented and filed. Subjective information alone seldom provides the confidence needed to make politically sensitive management decisions.

6. Overall Effect. Addressing overall effect of fire on wildlife for a given area that has burned is most easily approached by going from the general to the specific.

a. What was the original successional stage and structural condition?

b. What Life Forms or Guilds were associated with those preburn conditions?

c. What will the new successional stage and structural makeup be?

d. What Life Forms or Guilds will be favored by the new conditions?

e. How were species of management or public interest affected?

f. How may any obligate or otherwise sensitive species have been affected?

7. Sources. An increasing number of sources for assistance in developing monitoring programs are available. Only a few of the more readily available are listed here. Inventory and Monitoring of Wildlife Habitat (Cooperrider et al. 1986) contains a wealth of information. Species specific habitat guidelines have been developed for pronghorn (Yoakum 1980), sage grouse (Autenrieth et al. 1982) and a number of other animals. Thomas et al. (1979) outlines simple procedures for measuring and evaluating edge diversity. Estimating Wildlife Habitat Variables (Hays et al. 1981) is an excellent field-oriented guide that not only addresses procedures but offers estimates of time and cost involved with various techniques. Chapters VI and X of this Guide should be referred to for further considerations and direction on monitoring and evaluation.

E. Summary

Fire is a shock - frequently, nearly instantaneous - to the ecological setting involved (Huff et al. 1984, Lyon et al. 1978). Some wildlife species are able to adapt to the rapid change in environment and some cannot (Lyon and Marzluff 1984, Parker et al. 1983, Rotenberry and Wiens 1978, Wecker 1964). The habitat for some species is greatly improved, while for others it may be degraded if not eliminated, and there will be endless variation in between (Beck and Vogl 1972, Bendell 1974, Evans 1988, McGee 1982, Wolf and Chapman 1987). No fire - either wild or prescribed - is uniformly "good" or "bad." Effects are differentially imposed.

A righteous attempt at providing for desired fire effects through prescribed burning or evaluating wildfire effects on wildlife and its habitat requires an integrated effort of disciplines. An appreciation of the historical perspective can be invaluable. Contributions by plant or fire ecologists are essential - individuals may have the talent but not the title. Input from those with a thorough knowledge of fire is certainly important. Postburn management is absolutely critical. Obtaining good management necessarily requires close coordination with and commitment from specialists in range, forestry, recreation, and others.

Without adequate monitoring and evaluation, little knowledge can be gained and even less, shared.

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CHAPTER VIII - CULTURAL RESOURCES

By Dr. Richard C. Hanes

A. Introduction

Cultural resources include a range of different resource types. These resources include locations containing archaeological and architectural remains resulting from human activity in the prehistoric and historic periods; and locations of continued traditional use activities, primarily associated with areas of religious or traditional subsistence concern to Native Americans.

Prehistoric archaeological sites include artifact scatters at locations where tools were made, a series of depressions in the soil surface representing a pithouse village, pueblo ruins, and rock art panels where figures were carved or painted centuries ago. Historic period sites pertain to more recent activities. Examples include old cabins, early homesteads, trails, battlegrounds, early mining remains, and logging camps. The second category of cultural resources noted above includes traditional areas where soil or plants are collected, or ceremonies conducted for secular or religious purposes. In some cases, these areas coincide with locations where archaeological remains are found, but they are just as likely to be a spring, mountain, or other geographic feature not containing tangible reminders of past activities.

B. Principles and Processes of Fire Effects

Particularly important information concerning fire effects on cultural resource values has been developed by Peter Pilles (1982) of the U.S. Forest Service and by National Park Service programs (Kelly and Mayberry 1980). Much of the following information draws from those sources as well as others noted.

It is difficult to accurately assess the effects of prescribed fires or wildfires on cultural resources. One important factor is the widely varying responses of vegetation and soils to fire within the same burn area, or under the same prescription in different burn areas. At most cultural resource sites on public lands, artifacts are distributed on the soil surface, or buried within the soil, even when historic or prehistoric structures are also present. The amount of surface and subsurface heating depends upon the peak temperatures reached and the duration of all phases of combustion. The amount of subsurface heating is a function of a number of variables, including soil moisture content and coarseness, amount and distribution of woody fuels, occurrence of duff layer or other accumulations of organic litter, weather conditions, and fuel and duff moisture content. (See Chapter III.B.6., this Guide for a more detailed discussion of burn severity.) Fire behavior studies have shown that no clear relationship is currently known between surface temperatures attained in a fire and temperatures conducted below the soil surface. It appears that only a small percentage of surface heat penetrates the soil deposits, because soil temperature during a fire can decrease dramatically in just a few inches of depth. Smoldering and glowing combustion of both surface and subsurface fuels can be important contributors to heating of buried artifacts.

Few formal studies of the effects of fire on archaeological sites have been performed. Studies in the 1970's involved the Radio Fire in the Coconino National Forest near Flagstaff, Arizona (Pilles 1982),the La Mesa Fire near Bandelier National Monument, New Mexico (Armistead 1981; Traylor 1981), the Moccasin Mesa Fire at Mesa Verde National Park, Colorado (Switzer 1974), and the Dutton Point Fire at Grand Canyon National Park (Jones and Euler 1986). These were all wildfires, not prescribed fires. A handful of studies and recorded observations have been conducted in the 1980's, including experimentation with prescribed fires in the Cleveland National Forest in California (Pidanick 1982; Welch and Gonzalez 1982). The literature addressing the effects of fire and heat on archaeological materials is still very meager in quantity and largely unpublished. However, enough information exists to indicate that the effects are variable, depending upon the material that is heated and the level of heating attained.

Arguments are made that many of the prehistoric cultural resource sites have been exposed to fires, perhaps repeatedly, in the past. So why the concern over fires today except in the more obvious cases where perishable structures are involved? In addition to the rebuttal that we are likely dealing with cumulative information loss from repeated impacts, other important factors must be considered, including relative burn severity between historic and prehistoric fires, recent surface exposure of some ancient sites, and cumulative changes in erosion patterns.

A growing body of information, based on early historic accounts, ethnographic studies, and field fire history studies suggest fire was much more prevalent prior to implementation of fire suppression policies earlier this century. The higher frequency of fires earlier in time is at least partly attributed to aboriginal burning practices (Lewis 1973, 1985; Barrett and Arno 1982; Arno 1985; Gruell 1985). In areas where fires occurred frequently, the exclusion of fire has often led to levels of fuels higher than would have "naturally" occurred. Fires which occur now potentially have greater impacts on cultural resources because of the increased amounts of heat that can be released during burning.

Archaeological sites often contain a variety of cultural-related materials, including stone, bone, shell, ceramics, metal, glass, wood, leather, and other substances. The resultant combination depends on the technologies of the inhabitants, the specific activities being performed at that location, and the preservational characteristics of the setting.

1. Potential for Physical Damage to Materials. The effects of fire on these various materials, whether buried or on the surface, can vary significantly because of different inherent properties and locations where materials occur.

a. Stone. A commonly observed result of intense, high temperature fires is the occurrence of heat damaged stone artifacts. An example of such damage was presented by a very hot prescribed fire in California's chamise chaparral that resulted in temperatures over 700 F (371 C) at one location where archaeological materials had been placed to assess the effects (Pidanick 1982). Some chert chipped stone implements had shattered; other artifacts including obsidian items and grinding stones were heavily smudged. Artifacts placed at other locations where temperatures never reached 400 F (204 C) were unbroken and only lightly smudged. Laboratory experiments have demonstrated that the crystalline structure of many forms of silica-rich stone changes when heated above 700 F (371 C) (Purdy and Brooks 1971; Mandeville

1973). Beyond that temperature, stone will spall, crack, shatter, oxidize, or simply break from direct exposure to heat. Extensive heat spalling of lithic artifacts was observed in hot "spots" of the 1974 Day Burn in the Apache-Sitgreaves National Forest.

Many masonry pueblos in the Southwest are constructed with dressed sandstone blocks. Exposure to intense heat can lead to color changes through oxidation, severe cracking, spalling, and even crumbling as a result of burning away vegetation that has aided in stabilizing the remains through time (USDD-COE 1989; Traylor 1981).

Rock art sites, including those where designs are painted on stone (pictographs) and others that are pecked into stone (petroglyphs), are especially susceptible to damage by fire. When exposed to intense heat, painted designs can be soot blackened, scorched or completely burned away while petroglyphs on friable stone, such as sandstone or limestone, can exfoliate (Pilles 1982; Noxon and Marcus 1983).

b. Ceramics. Pottery is another class of artifact that may be seriously affected by fire (Burgh 1960). Pottery is made by subjecting fabricated clay vessels to intense heat where sintering and other physical and chemical changes give it clastic properties. However, fire of long duration or high intensity may refire prehistoric or historic ceramics, which can recombine the constituents, oxidize certain elements, burn out carbon paints and cause increased brittleness. Smudging or the deposition of surface carbon residue also may make it difficult to identify and date ceramics.

In the Apache-Sitgreaves fire, ceramics became highly vitrified and appeared as hard black sponges. Similarly, after the 1972 Mesa Verde National Park wildfire, spalling and discoloration of ceramics was noted. The primary impact observed at the Dutton Point Fire was smudging of shards that may disappear naturally after years of weathering. In summary, fire can burn pot shards, affect their chemical composition, change their colors, and alter their decorative paints and glazes, making identification of styles and manufacturing techniques difficult in some cases. (See also Pilles 1982, p. 6.) The more substantial changes begin to occur with temperatures of 925 F (496 C), a threshold higher than for stone.

c. Organics. Objects made or manipulated by a site's occupants are not the only materials used to reconstruct a scenario of activities that were performed at a given location. Many sites contain shell and bone, giving evidence about the nature of prehistoric diets. When exposed to a high level of heat, shell will become calcined and very friable. The effects of fire on bone have yet to be thoroughly investigated, but at Custer's Battlefield, old bovine bone fared very poorly compared to stone and metal objects (Scott 1987). Pollen grains, used for paleoenvironmental as well as dietary studies, are destroyed at temperatures above 600 F (316 C) (Traylor 1981). Artifacts made of organic materials such as woven baskets, wooden digging sticks, rawhide cordage, and fur clothing are usually very fragile in the archaeological record and are highly susceptible to charring and consumption at very low temperatures (Seabloom, Sayler, and Ahler 1991).

d. Metal and glass. Not much is known about the effect of wildland fire on inorganic materials largely associated with historic period sites in the West, such as metal implements and glass bottles or beads. A recent North Dakota prairie fire study found that small lead and glass items became fused or melted when subjected to ground surface heating (Seabloom, Sayler, and Ahler 1991).

2. Effects on Dating Techniques. The archaeologist today has several techniques available for deriving absolute dates of site occupation (Michels 1973). In addition to the impacts to artifacts and material types noted above, materials used for several dating techniques also may be affected by fires (Traylor 1981, Pilles 1982).

a. Tree rings. Tree ring records preserved in wooden beams or other construction materials used in dendrochronologic studies are highly susceptible to fire.

b. Radiocarbon. Charcoal samples used for radiocarbon dating can become contaminated from ash and charcoal produced by a fire, and could yield a date more recent than the true date of the sample.

c. Thermoluminescence. Pottery fragments, when subjected to thermoluminescent dating techniques, could provide significantly younger dates than expected after being exposed to high heating episodes.

d. Obsidian hydration. Obsidian hydration is a dating technique that measures the amount of moisture present in the external surface of an obsidian artifact. Moisture is absorbed from the atmosphere by freshly flaked obsidian surfaces at a constant rate. Heat from a fire (apparently at only high levels of heating) can alter the moisture content, thus yielding an inaccurate date or erase the record altogether.

e. Archaeo-Magnetic. Archaeo-magnetic dating measures the orientation of electrons in stones from prehistoric hearths and compares this data to changes in the earth's magnetic field over the past several thousand years. If these features are subjected to temperatures above 975 F (524 C), they can give erroneous information by releasing electrons to realign with the current magnetic fields of the earth.

f. Cation-Ratio. Cation-ratio dating is a new technique for dating rock art through chemical analysis of surface varnish. It is possible that smoke from a fire could alter the ion structure of these features, thereby preventing accurate dating.

3. Impacts of Burn Area Preparation and Mechanical Suppression. The most dramatic and predictable effects of fire activities on cultural resources result from the use of equipment in burn area preparation, fire suppression, or burn area rehabilitation work. Impacts from these activities are also the most preventable. Pilles (1982, p. 6) has noted that:

Studies of the La Mesa Fire at Bandelier National Monument and the 1977 fire on the Coconino National Forest found that heavy equipment used during suppression activities and mop-up operations had a greater effect to archaeological sites than did the actual fire itself. Artifacts are broken and displaced and small sites can be completely destroyed by one pass of a bulldozer blade. Depending on the depth of a blade cut and the proximity of site features to the surface of the ground, buried features, such as caches, burials, and firepits, can also be destroyed by bulldozer work. During both the Radio and La Mesa forest fires, about 15 percent of the archaeological sites in the area were damaged by heavy equipment. In the La Mesa Fire, however, most sites were damaged during mop-up and restoration activities after being initially avoided by fire suppression activities. Both instances point out the importance of timely planning and continued coordination with archaeologists for projects involving the use of heavy equipment.

Obviously, burn area preparation could cause damage to cultural resources if mechanical equipment is used. Additionally, construction of heliports, vehicular traffic, and hand construction of firelines can impact cultural values. Postfire erosion control measures such as mechanical seedings, contour trenching and furrowing, and construction of sediment traps are restoration activities that pose significant threats to archaeological sites.

4. Erosion and Looting. Loss of ground cover normally leads to greatly enhanced visibility. In many regions of the West, wildfires have long been noted for their propensity to expose sites previously difficult to find; consequently large numbers of people can be found cleaning the surface of diagnostic tools and excavating sites where archaeologically rich deposits are discovered following fires. Similar behavior has been noted of fire crews who had not previously been advised of the significance of such activities (Traylor 1981). This is of increasing concern, as the illegal collection and excavation of archaeological materials has escalated during the past 30 years. The water holding capabilities of litter, duff and surface soils are also reduced by fire, which sometimes generates erosion hazards.

C. Resource Management Considerations

The preceding sections briefly describe a diverse array of impacts that fire and associated fire management activities pose for cultural resource values. However, many of the heating effects only occur at significantly high temperatures and many associated on-the-ground activities can be planned ahead of time. Consequently, the fire process can be managed to minimize harmful effects and serve as a useful tool in managing cultural resources.

1. Fire Planning. The most effective means of addressing fire effects is through development of a management plan that takes the above concerns into account. (See Anderson 1985.) Various facets of the land management planning process may be used. The cultural information may be provided in a prescribed fire plan, a wilderness management plan, a general resource management plan, or, for areas that are of particularly high cultural resource values, a cultural resource management plan. All agency cultural resource management plans should include a section on the effects of fire suppression. Regardless of the type of plan employed, it should provide information about the number, type and distribution of cultural resources, known or predicted to occur, in a proposed project area (Pilles 1982, p. 8.) and how susceptible these resources are to impacts from fire. Are there abundant cultural resources in the area? Are there historic settler's cabins or sawmills present that could be destroyed by fire? Has the area ever been examined by a professionally qualified archaeologist? Are there any Native American concerns that might be affected by a prescribed burn? Are there any areas considered highly religious? Would burning at a particular time of the year disrupt traditional religious pilgrimages, plant collecting, or hunting practices in the area?

Prior to prescribed fires or the next wildfire season, baseline cultural resource information should be gained minimally through an updated synthesis of existing information, contacts with the appropriate Indian tribes, coordination with the State Historic Preservation Office, and inclusion of information from other knowledgeable sources. Further information may be gathered through field reconnaissances, sample field surveys, or detailed individual site assessments. From the information gathered, areas of unusual sensitivity or highly significant sites may be identified on maps and their vulnerability to fire effects assessed. Management direction regarding fire activities may then be established and the resulting information provided to those in charge of planning and directing field activities. The management direction for wildfire suppression and prescribed fire projects should be coordinated with the State Historic Preservation Office, again, to streamline any required Section 106 consultation needs that may arise when fire activities are imminent. The plans should include procedures for training fire crews about the illegality of artifact collecting and the associated stiff penalties, and for educating crews to identify sites so that damage to these resources can be avoided during fire suppression activity.

2. Maintaining Historic Plant Communities. Constructive use of fire also can be identified in terms of reestablishing the historic environmental context of important cultural resources and maintaining certain Native American traditional practices (Larson and Larson 1988). Examples of the former case includes restoration of grassland from recent pinyon-juniper invasion at a historic fort site and removal of brush thickets from historic trails, thus opening them to recreational use (Pilles 1982).

In the case of Native American needs, burning can be used to promote the growth of certain plants used for food, medicine, or craft manufacture. An outstanding case is presented in California where prescribed burning by the U.S. Forest Service allows growth of new plant shoots. This new growth has the proper strength and resiliency for the Yurok tribe to use in weaving baskets and hats for tribal ceremonies and as traditional apparel (Pilles 1982). Such activity is helping revitalize certain areas of traditional Indian culture.

3. Use of Prescribed Fire to Minimize Potential Damage from Wildfire. As noted above, the heating effects of low temperature prescribed fires appear to be substantially less than the effects of much hotter wildfires. Archaeologists can learn much from fire history studies and effects on soil properties. Knowledge of the frequency of prehistoric fires would likely indicate the possible cumulative effects on cultural resources, with high fire frequencies likely associated with "cool" fires and minimal impacts on resources.

a. Subsurface resources. During prescribed fires, effects of heating are usually not severe. Most artifacts are insulated from the heat of a fire by an earth cover and ideal temperatures for most prescribed fires are less than those that critically affect artifacts. If a condition is present of low fuel loads or a fire occurs with higher duff or soil moisture content, there is less potential for heating. However, if fire burns with high heat per unit area, then damage to surface artifacts is likely. Also, if a fire is of long duration, damage to buried artifacts is more likely.

In some areas fire suppression policies of the past century have led to "artificially" high fuel loads, thus increasing the potential for damaging cultural resources through severe heating when fires occur. Additionally, encroachment of shrubs and/or trees allows deep litter layers to accumulate and increases the potential for longer duration fires. In some situations, an agency may need to use prescribed burning or some other fuel load reduction strategy to attain its mandated mission for protecting cultural resources.

b. Aboveground structures. Historic period and prehistoric architectural sites pose special concerns. The historic period sites were created either during, or just before, the period of enforcing strict fire suppression policies without the augmentation of prescribed burns. Consequently, the sites have not been subjected to any form of fire, and preservation in many cases may be very good. Old buildings and ruins constructed of wood are obviously susceptible to destruction by fire. Burn prescriptions will need to be designed to avoid impacts on these types of cultural resources yet reduce the fuel load buildup around them. Possible prescriptions might be to put a fire line around sites with wooden structures so they are not burned; modify project boundaries to avoid rock outcrops where rock art is located; remove combustible materials from the surface of a site so the fire will either burn around it or burn with "cool" temperatures above it; shift the location of a control line, staging area, or utilized water source to avoid a site; change the dates of the burn so it does not impact Native American use of the area; or simply have the archaeologist monitor the burn while it is in progress.

It can be concluded that by burning under favorable conditions where burn severity may be controlled and monitored, management of vegetative communities through fire can be pursued while enhancing the agency's ability to protect cultural resources.

D. Methods to Monitor Fire Effects

The above discussion briefly addresses a number of complex issues for which few objective data are available. Most information thus far has been collected in association with major wildfires occurring in areas of heavy fuel buildup. Very little quantification of the effects of fire on archaeological sites has been documented, and little has been reported of prefire site conditions. There is a great need for experimentation, particularly utilizing prescribed fire conditions. In addition to recording artifactual and site preburn and postburn information, detailed documentation of fuel load, fuel and soil moisture, weather, fire rate of spread, temperature at and below the soil surface during combustion, duration of heating, and other fire factors needs to be accomplished. In anticipation of a fire, half of a site could be excavated prior to the fire, and the remainder excavated afterwards. By employing such procedures, the effects of the burn on various aspects of the archaeological record could be evaluated, and correlated with the behavior and severity of the fire.

More study is needed to determine the full range of effects to cultural resources by wildfire and, especially, controlled burning projects. In order to accomplish this, a variety of experiments in different environmental settings with different kinds of cultural resources needs to be done. Only by observing fire effects in a variety of conditions can we know for certain that there is no significant or irreplaceable loss to cultural resources as a result of prescribed fire programs or the degree of damage posed by wildfire. To accomplish this goal, land management plans can commit specific cultural resource sites to "management use" for fire effects experimentation.

In addition, furnace tests on archaeological materials are needed to establish controls for comparison of field test results. Furnace tests can assess the effects of different temperature levels and heating periods on specimens of ceramics, metal, glass, bone, shell, and stone. Such information can aid in documenting actual fire effects on artifact friability, weight, and visible characteristics (e.g., color, form, decorative patterns, and trademarks).

Experiments, such as those described above, would provide an ideal opportunity for interagency cooperation and could assess the relative success of the fire management procedures and philosophies of different agencies. The value of such cooperation has already been demonstrated by studies of the Radio Fire and the La Mesa Fire, conducted by the Coconino National Forest and the Southwestern Regional Office of the National Park Service. These two studies are the main data sources available for assessing the impacts of fire and fire management activities on cultural resources. An interagency clearinghouse for assembling data and reports pertaining to fire effects on cultural resources could greatly assist the otherwise disjointed approach taken by the various organizations.

As acknowledged above, visibility of cultural resources is greatly enhanced by burning away the ground cover. A 1977 tundra fire in Alaska removed shrub growth, revealing prehistoric stone-lined pits where none were previously visible (Racine and Racine 1979). Wildfires in the early 1980's in pinyon-juniper woodland areas near Las Vegas and Carson City similarly resulted in the discovery of prehistoric rock ring features where none were previously known. The Las Vegas rings were likely associated with past pinyon nut caches; the Carson City features are possibly remains of habitation structures. In Mesa Verde National Park, prehistoric farming terraces were revealed when fires burned away the dense underbrush. Before this, archaeologists were not aware of the abundant existence of such features in the Mesa Verde area. Consequently, the coordination of prescribed fires with postfire archaeological surveys would be beneficial to the agencies in achieving goals for two programs. The benefits to the cultural resources program are obvious in the greater efficiency achieved in conducting inventory efforts. Also, patterns identified in heat damage to artifacts by the above furnace and field studies have promise to aid in the interpretation of heat damage sustained by artifacts in early historic and prehistoric times (Seabloom, Sayler, and Ahler 1991).

E. Summary

Damage to cultural resources posed by wildfires and prescribed fires can be severe, ranging from chemical alteration of cultural materials to exfoliation of building materials and rock art panels. However, almost all impacts can be avoided through advanced planning. Protective measures can include removal of high fuel loads by hand or prescribed fire, careful use of fire breaks for avoiding fire effects on wooden structures and other highly susceptible resource values, and use of archaeological monitors on wildfires in sensitive areas to avoid fire suppression damage.

The experiments and observations thus far conducted indicate that cultural materials below the surface, unless directly exposed to a burning duff layer or burning underground roots, normally do not sustain significant damage, if any at all (Traylor 1981). Though the Cleveland National Forest found that many surface artifacts were damaged by a prescribed fire in chamise chaparral, no subsurface artifacts were affected (Pidanick 1982). Measurements taken at the prescribed fire documented temperatures in excess of 800 F (427 C) at the ground surface, but only 100 F (38 C) at 5 centimeters (2 inches) below the surface. Obviously, the magnitude of fire effects on the soil and its contents is proportional to heat penetration. In conifer forests, temperatures of 200 F (93 C) have been recorded one/half inch (1.3 centimeters) deep in the soil, with duff layers considerably above that figure. Obviously, such heating depends on the thickness of the duff layer, duff moisture content, amount and moisture content of large diameter dead woody fuels, and soil type and its moisture content. Given current knowledge of fire effects on cultural resources, it is apparent that fires involving larger fuel loads, longer duration burns, and large total heat release pose significantly greater hazards to cultural resources, than fires with short duration "cool" combustion temperatures.

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CHAPTER IX - PREFIRE AND POSTFIRE GRAZING MANAGEMENT

By Ken Stinson

A. Introduction

The impacts of grazing management before and after a fire have a dramatic effect on the response of vegetation to the fire, and what one can expect in the long term. The history of management on burned areas has included such things as:

1. Seeding introduced species for increased livestock or wildlife forage that resulted in additional management conflicts.

2. Short-term rest from livestock grazing to allow seedling establishment.

3. Some followup long-term grazing management but with heavy to severe utilization rates.

4. Conducting prescribed fires to temporarily increase production on an allotment to avoid adjustment in grazing use.

5. Temporarily increasing utilization by improving palatability of rank plant species such as Tobosa grass *(Hilaria mutica)*, sacaton *(Sporobolus spp.)*, and sprouting browse species.

6. Grazing use in an area during a prefire rest period required to accumulate adequate fuel to carry a fire, resulting in a subsequent prescribed fire that could not meet objectives.

The need for increased intensity of grazing management on burned areas can be understood by realizing the potential change in the plant community and associated animal response that can result from a burn. If one is not willing to commit to long-term grazing management, prescribed fire should not be considered or approved.

B. Principles of Prefire and Postfire Grazing Management

1. General Need for Improved Management. "Prescribed fire should not be a substitute for good range management. A problem rooted in inappropriate range management practices may not be corrected by vegetation treatment. In these instances management should be altered prior to application of prescribed fire. If livestock have premature access to the burn, the full benefits of the prescribed fire may not be realized and negative impacts may occur unless management of the livestock is included in the plan" (Bunting et al. 1987). "Followup management is the most important aspect of a controlled burn and must be provided for in the overall management plan" (Smith 1981). "Grazing management following burning may significantly affect the degree of change in forage species productivity and possibly the composition of the postburn vegetation" (Smith et al. 1985). The need for management of livestock use on a burned area is most critical the first growing season after fire, particularly in plant communities of arid and semiarid regions (Trlica 1977). Livestock use must be managed on the sites of both prescribed fires and wildfires.

Fire results in changes of animal behavior including grazing pattern, preferences, utilization rates, forage consumption, and frequency of grazing use. Wild and domestic animals are attracted to recently burned areas resulting in greater utilization of the burned area than surrounding vegetation (Pase and Granfelt 1971; Bunting et al. 1987). Cattle, horses, and sheep usually have the greatest impact. Grazing animals frequently concentrate on a burn because the herbage or browse is more accessible, palatable, and nutritious (Wright and Bailey 1982). Plant growing points may also be exposed, increasing the likelihood of damage from a foraging animal. Carbohydrate reserves of sprouting plants are usually depleted because of energy required to regenerate after a fire. Repeated use of these plants can cause considerably reduced vigor, and sometimes death of key forage or browse species. (See VI.B.4.b. (1) and (2), this Guide, for a more detailed discussion of carbohydrate reserves.)

Grazing in forested areas can help forest regeneration if competing plant species are grazed, or hinder regeneration if tree seedlings or sprouts are eaten or trampled. Extensive damage to young conifers from trampling has occurred in clearcut areas that were seeded to grasses (McLean and Clark in Urness 1985), and has been observed in burned clearcuts where postfire growth of grasses and sedges attracted livestock (Zimmerman 1990). The presence of larger diameter logging slash can discourage livestock and big game use.

2. Rest and Deferment.

a. Prefire. Prefire rest from grazing is required on many range sites to allow the accumulation of enough fine fuel to carry the fire. This is important in shrub/grass and pinyon-juniper types as well as in forested areas, particularly aspen ecosystems where grass and shrub litter may be the main carrier fuels (Jones and DeByle 1985). Allowing grazing, sometimes even for a short period of time during the year before the fire, can remove enough fuel to limit fire spread. A patchy fire may occur, or the fire may not be able to carry at all, and in both cases fire treatment objectives are not met. Prefire rest may also be required to restore levels of plant carbohydrate reserves on heavily grazed sites, shrub dominated sites, or where shrubs are very old and in poor condition. More than one year of prefire rest from grazing may be required to obtain adequate fuel to carry the fire, or to achieve the desired postfire response, especially in areas with severely depleted understories.

b. Postfire. The amount of nonuse necessary after a fire varies considerably with the vegetal composition, site conditions, and objectives of the burn (Bunting et al. 1987). The initial concern following burning is the restoration of plant vigor and seed production. Generally, at least two growing seasons rest are recommended (Pase et al. 1977; Wright et al. 1979; Blaisdell et al. 1982), both to allow reestablishment of preferred species and to deter reinvasion of shrubs. Bunting (1984) usually recommends rest for one year and deferment of grazing until after seeds have ripened the second year, if the range is otherwise in fairly good condition. Some species of sprouting shrubs take much longer than two years to recover, such as bitterbrush, and rest for a longer time period is necessary if reestablishment of browse species is an objective.

"Anticipated results from the best prescriptions for a burn may be seriously modified if destructive grazing practices are allowed afterwards. Only a small amount of forage is produced the first year, and grazing may cause serious damage to soil and desirable perennials. Despite the apparent abundance of green herbage, most plants are low in vigor and will be further weakened or destroyed by grazing. Furthermore, grazing will disturb the inadequately protected soil and allow increased water and wind erosion. Protection through the second growing season will allow restoration of vigor and the typical heavy seed production of perennial grasses and forbs. However, after seed dissemination, light grazing may serve a useful purpose in helping to plant the seed" (Blaisdell et al. 1982). Early establishment of a good grass cover, and subsequent conservative management, virtually assures soil stability and low sediment yields on moderate slopes (Pase et al. 1977).

Grazing in the early growing seasons immediately following burning may accelerate sagebrush reestablishment. This is particularly true when areas with dense sagebrush and low production of grasses are burned (Laycock 1979; Smith et al. 1985). This may be desirable if sagebrush is an important habitat component for wildlife species. Grazing systems that provide for periodic rest during the growing season will extend the useful lifetime of the project (Britton and Ralphs 1979; Smith et al. 1985).

Evans (1988) gives a general rule that newly seeded areas should not be grazed for at least two years following seeding. Low potential sites and those seeded with slow developing and slow growing species may require as many as four seasons of nonuse to develop into productive stands. Below average amounts of postfire rainfall also can retard the recovery of a site.

3. Proper Followup Grazing Management. "Improvement of an overgrazed range--that is, improvement in range condition--starts with a decision to stock the pasture at a rate to permit improvement" (Dyksterhuis 1958). Burning an area that is in poor condition because of overgrazing can temporarily increase production of desired species. However, the improvement will be short-lived if grazing practices remain unchanged. "Various combinations of rotation land deferment. . . have all proven to be successful where such factors as range condition, kind of livestock, stocking rate, season, and intensity were given proper consideration. Rate of stocking--balancing numbers and time of grazing animals with forage resources--is the most important part of good grazing management ... Seemingly there has been over-optimism in judging grazing capacity and allowable use, which has been an important factor in range deterioration . . . It has become increasingly apparent that former utilization standards are often several times more than can be tolerated continuously, and that reduction in livestock numbers is often necessary to correct unsatisfactory conditions" (Blaisdell et al. 1982).

Holechek (1988) researched and published utilization guides by precipitation zone for different range types in the USA. The recommended average degree of use of the key species varies from 20 to 50 percent with the upper levels only on good condition ranges or for dormant season grazing. Heavy grazing invariably leads to a gradual loss in forage productivity and vigor, high death losses, and higher costs for supplemental feed in drought years. Pechanec, Stewart, and Blaisdell (1954) found in the sagebrush-grass type that proper followup management, i.e., protection from livestock use the first year, and light grazing the second year with proper stocking thereafter, resulted in increased grazing capacity 9 years later. Capacity on this area was increased by 83 to 106 percent, but there was only a 4 percent increase without this management. The area with proper management had five sagebrush plants per 100 square feet (9.3 square meters), compared to 55 plants per 100 square feet on the area without the above management.

On desert grasslands postfire rest must occur, and careful, conservative management followed until the weakened grass cover has completely recovered (Pase et al. 1977). Postfire recovery of browse species in these arid areas may take much longer than on more mesic sites (ibid.) A common goal for all grazing systems should be reduction of damage from grazing while promoting beneficial effects, and many systems appear equally effective (Blaisdell et al. 1982). Many combinations have proven to be successful where such factors as range condition, kind of livestock, stocking rate, season, and intensity were given proper consideration.

4. Economic Considerations. One of the primary reasons for the interest in using prescribed fire and limited control of wildfire is the perception that fire is a cheap brush control treatment. Smith (1981) states that prescribed burning provides an inexpensive brush control method, but labor will greatly increase the cost of prescribed burning, so the planning process should emphasize practices (such as fuel breaks) that will reduce labor needs to a minimum. He also lists one disadvantage as the risk of fire escaping and consuming valuable forage, ensuing property damage and danger to lives, resulting in expensive suppression costs and civil suits.

Bunting et al. (1987) suggest that selection of area to be burned will dictate many of the economic variables such as fire prescription and characteristics and whether it achieves its objectives . . . the higher potential sites produce the highest benefit. He also states that burning during the spring with snow lines and increased fuel moisture on varying aspects adjacent to the proposed treatment area may aid in fire control and reduce overall cost. The limited burn size, however, may increase the amount of time and personnel required for ignition resulting in higher average costs per acre or not achieving the planned objectives. Bunting says that economics is also a factor in determining the size of fires. The costliest portion of conducting prescribed fires is establishing and burning out the fire lines. The smaller the size, the greater the perimeter per unit area. Without natural fuel breaks, an extensive system of fire lines may have to be established to restrict the fires to the desired size. This often makes the prescribed burns economically unfeasible.

From an economic standpoint, spring burning is cheaper as it can be accomplished with fewer individuals and without firebreaks in some situations (Blaisdell et al. 1982). West and Hassan (1985) state that the highest potential for prescribed burns is on sites in good condition. Haslem (1983) provides several guidelines to maximize returns from burning including realistic prescriptions, treating manageable units, using livestock use for controlling escapes, use of natural control barriers, and use of test burns. Smith (1981) states that followup management is essential in extending the fire's useful lifetime.

Young and Evans (1978) state a general rule that one must be able to step from one bunch grass plant to another to have a reasonable chance of enhancing the site by recovery of existing plants. Bunting (1984) also notes the bluebunch wheatgrass response is from existing plants for the first 3 or 4 years after a fire. Dramatic increases in numbers of plants of exotic annual species can occur after fire, particularly if the existing bunchgrass community was in poor condition or many of the plants were killed by the fire. This potential for site invasion must be considered along with the above guidelines when deciding if a site can recover without artificial seeding.

5. Examples of Different Intensities of Grazing Management. Many different grazing management strategies have been implemented after burns, however, few have been intensively monitored to determine their impacts on fire effects. Two prescribed burns in northwest Wyoming, which escaped into adjoining grazing allotments, were monitored during 1987 to provide data on effects of postfire grazing management on vegetative response.

a. Blue Creek Coordinated Resource Management Plan (CRMP). In 1984, the operators agreed to a CRMP with the Wyoming Game and Fish Department and the Bureau of Land Management. The area is located south of Meeteetse, Wyoming, in the 15 to 19 inch (38 to 48 centimeters) precipitation zone at the 7,800 foot (2,377 meters) elevation. The vegetation type is composed of limber pine *(Pinus flexilis)* and mountain big sagebrush *(Artemisia tridentata vaseyana)* on a shallow loamy range site. Key graminoid species include Idaho fescue *(Festuca* *idahoensis)*, green needlegrass *(Stipa viridula)*, and rhizomatous wheatgrasses. The growing season in this area is from mid-May until about September 1. The adjoining allotment received heavy livestock use from the first of July until snowfall each year. The unburned site had a mountain big sagebrush canopy cover of 60 percent and produced an estimated 700 pounds per acre (785 kilograms per hectare) of annual sagebrush growth.

The planned actions started in 1981, including nonuse of livestock grazing, conducting prescribed burns, and fencing for grazing strategy implementation. In the year of the prescribed fire, snow left the area earlier than normal. The prescribed burn was conducted on April 3, 1985. The fire escaped across the allotment boundary fence into the adjoining allotment, burning about 20 acres (9 hectares) of mountain sage type. About 15 acres (7 hectares) of the escaped fire area were deferred from grazing for two growing seasons by a temporary electric fence, that is, no grazing occurred during the growing season. The original intent was to exclude animal use entirely but elk tore down the electric fence in September both years.

Herbaceous production data was collected during July 1987 in four adjoining sites. Weight estimates were made on ten plots, and two plots were clipped to obtain a correction factor. The study included one transect in the Blue Creek allotment that received no grazing for 4 years before the prescribed fire, and no use in the 27 months after the prescribed fire when the production data was collected. There were three areas studied in the adjoining allotment, all of which were grazed in the years before the prescribed fire. One area was unburned; the second received season long grazing in 1985 and 1986; and the third site was the fenced area where grazing was deferred throughout two growing seasons. Table IX-1 details the site and species production data that was collected.

Table IX-1: Herbaceous Production (pounds/acre dry weight) - Blue Creek.

Species	Unburned	No Rest	Deferred	Nonuse
Idaho Fescue	280	74	568	1,056
Rhizomatous wheatgrasses	19	447	210	762
Green needlegrass	24	51	182	103
Other Grasses and Forbs	590	920	828	713
Forbs	NA	579	1140	859
TOTAL	913	2071	2828	3493

All burned areas had higher grass production than the unburned area. However, the areas with deferred grazing and nonuse had much higher production of Idaho fescue, the preferred species. The nonuse area had twice the fescue production of the area that was grazed the year before the fire and deferred for two seasons afterwards. The unrested burned area had one-quarter of the Idaho fescue as the unburned area. Higher postfire palatability of this preferred species likely resulted in higher utilization rates by livestock, causing it to all but disappear from the site.

b. Orchard-Woods allotments. The second study area is located south of Ten Sleep, Wyoming, in the upper 10 to 14 inch (25 to 36 centimeters) precipitation zone at the 6,800 foot (2,073 meters) elevation. Vegetation was dominated by mountain big sagebrush, bluebunch wheatgrass *(Pseudoroegneria spicata)*, green needlegrass, and Idaho fescue. The permittee for the Orchard Ranch was conducting a prescribed burn on September 14, 1983, and the fire escaped into the adjoining Woods Allotment. The Orchard pasture had received light to moderate grazing with a deferred rotation strategy for two years prior to the fire and was rested for two growing seasons afterwards. The adjacent Woods pasture received heavy season-long grazing prior to the fire, and was deferred until seed ripe the first two seasons after the burn. Herbaceous production data was collected on July 30, 1987, from both sides of the division fence by clipping ten plots (Table IX-2).

Table IX-2: Herbaceous Production (pounds/acre dry weight) - Orchard-Woods.

Key Species	Woods (Deferred)	Orchard (Rested)
Green needlegrass, Bluebunch wheatgrass, Idaho fescue	131	447
Other Grasses and Forbs	1,648	864
TOTAL	1,779	1,311

Total production on the deferred Woods allotment was higher than on the Orchard area. However, much of this production was weedy grasses and forbs. Production of the three preferred grass species on the Woods allotment was only one third of that on the Orchard allotment which had been rested after the prescribed fire.

c. Management implications. The primary implication of the preceding examples is that in order to increase production of late successional species, there must be a commitment to rest after the burn and proper grazing management in the long-term. The two growing-season rest after a burn greatly speeds the recovery and improvement of the key species. If a burned area is not rested, the extra moisture available after the sagebrush or other shrub and tree species are eliminated is used by rhizomatous grasses, or early successional grasses and forbs, depending upon what species are present before burning. If there are sprouting shrubs present that are not used by livestock such as rabbitbrush, they can become dominant in the community. Lupine, which is a legume, will take up the extra moisture in the mountain sage type for the first two seasons if the late successional grass species are damaged or lacking in the understory. The lack of sagebrush invasion into the burn sites on Blue Creek shows the importance of maintaining the maximum vegetative ground cover and vigor to help slow the recovery of sagebrush seedlings on the site. It can be expected that forage would continue to increase on these sites because peak production on a sage site generally does not occur until the third to fifth year after a burn. An additional implication for prescribed fire is that increased production of herbaceous species does not necessarily mean that the site is enhanced, if, as on the Woods pasture, much of the production is composed of annual weeds and rhizomatous grasses.

C. Resource Management Considerations

1. Fire Effects. The effects of fire on plants and their response characteristics are described in detail in Chapter VI, this Guide. The following impacts and changes must be considered in planning proper site management to obtain the desired fire effects.

a. Damage to key forage and browse species by repeated heavy utilization by animals or burning is very similar; therefore, many areas are impacted by fire and then again by grazing and/or browsing animals.

b. Increased palatability and accessibility of grasses, forbs, and shrubs, influenced by the green period, nutrient content, growth form, and removal of dead material, occurs during the first few growing seasons after a burn.

c. Carbohydrate reserves of burned plants are lowered the first few seasons after a burn.

d. Fire effects result in changes of animal behavior including distribution, utilization rates, forage consumption, and frequency of use.

e. Prefire and postfire grazing management largely determines the benefit/cost ratio because of its considerable influence on the life of the beneficial aspects of the burn.

2. Plant Maintenance Factors. Little research has been conducted to determine the best long-term management practices for burned areas. However, the findings from plant ecology studies conducted over the past 60 years can be applied. The following factors should be considered to determine grazing management requirements:

a. Plant community health (carbohydrate reserves for plant vigor and recovery potential).

b. Composition of plant species that occupy the site and their successional position.

c. Recovery period required by species after burning for vegetative, root, and reproductive growth.

d. Utilization limits for species and season of grazing. A key factor in range deterioration has been overly optimistic estimates about the amount of allowable use that an area can sustain. The research literature gives a range of 20 to 40 percent utilization of annual growth during the critical growth period and 40 to 60 percent during the plant dormant period depending upon species and management objective. Use at higher levels can cause deterioration of the plant community. **e.** Site potential, which considers the range site or habitat type description.

f. Plant species morphology and reproductive mechanism.

g. The type of grazing and browsing animals that use the site, both wild and domestic, and rodent or insect use.

3. Length of Postfire Rest Period. The length of the period of postfire rest from livestock use depends on these factors:

a. Ecosystem type and ecological condition before burning.

b. Vigor of vegetation prior to fire.

c. Season of fire.

d. Growing season conditions, including temperature and precipitation, prior to and following burning.

e. Whether establishment of new plants is by seed or sprouting. Seedlings require a longer rest period to become resistent to grazing damage. Browse species often require second year growth before producing seeds.

f. The management objectives for the area. For example, the length of postfire rest may vary significantly for the same area depending upon whether the area is being managed primarily for range, wildlife, forestry, or recreation, or a mix of these activities.

4. Summary Recommendation for Rest. Postfire rest from grazing is required on both prescribed fires and wildfires, on seeded areas and unseeded areas. The length of the period of rest from grazing is dependent upon accomplishment of measured objectives for the area. General recommendations are:

a. Prefire.

(1) At least one growing season of rest before a prescribed burn is needed on many sites to increase both root reserves and fine fuels needed to carry fire.

(2) Severely depleted sites may require several years of rest before burning in order for key plants to regain vigor and reproductive capabilities.

b. Postfire.

(1) Burned areas should be rested until a good ground cover and a litter layer are present to provide soil and watershed protection.

(2) One growing season of rest may be adequate on some highly productive or high condition sites after a low severity fire. A minimum of two growing seasons rest is recommended for most burned areas.

(3) Areas under intensive grazing management can be grazed immediately after a fall-winter burn to harvest some unburned vegetation within the unit. This short use period prior to regrowth could assist in nutrient cycling, roughing of the soil surface, and breaking of any sealed ash layers. Because this use can also result in physical damage to the plant roots and crowns, it should be closely monitored and occur during a short time period. Time control grazing may be used to help accomplish postfire objectives if proper consideration is given to animal impacts and plant community recovery periods.

(4) Sites that are burned to increase utilization of unpalatable species should be grazed immediately after the fire while the undesirable plants are young and actively growing.

(5) Heavy utilization grazing of an area by wildlife or wild horses will require further rest from permitted livestock if their numbers cannot be controlled. Wild horses are difficult to move from their normal territories but any water close to the burn area can be regulated, especially during the first few growing seasons. Wildlife numbers can be controlled by harvesting excess animals, although this is only a feasible management strategy in the event of an extremely large wildfire.

(6) Below normal precipitation may delay vegetative recovery. A burned area should be inspected to determine if it is ready for grazing. It cannot be assumed that vegetation is ready for grazing just because the prescribed period of rest has occurred. The degree of accomplishment of measured objectives should be the most important criteria in determining the length of the postfire rest period.

(7) If recovery of wildlife browse is a key objective, the length of the postfire rest period may need to be much longer, and permitted levels of utilization by livestock may be much lower, than if target species for an area are grasses and forbs to be used by livestock.

c. After postfire rehabilitation. If postfire rehabilitation has been conducted, livestock should not be allowed back onto the burned area without evaluating whether rehabilitation objectives have been met. Postfire rehabilitation considerations are discussed in Chapter VI.C.6.a., this Guide.

5. Effects of Management Strategy. The commitment to long-term grazing management on burned areas is vital for real long-term improvement in plant productivity and composition. Determination of desired plant community objectives is necessary before the grazing strategy can be decided. Many sites proposed for burning are in poor condition or have mature stands of trees with little understory vegetation. These sites require long periods of time to progress through successional changes to meet objectives. If introduced plant species are seeded on the burned area, a grazing strategy must be designed to meet their survival needs. Seeded sites may have to be fenced separately from native rangeland due to phenology and palatability differences.

Effects of fire and grazing management cannot be easily separated; therefore, fire effects on vegetation should be monitored and evaluated both in the short term (prior to start of grazing or at the end of second growing season) and the long term (after two cycles of the grazing strategy or 8 to 10 years). The short-term evaluation assesses achievement of fire treatment objectives, while the long-term evaluation considers the attainment of desired plant community objectives.

Specific grazing strategies must be designed to meet key species requirements and land use planning objectives. These general principles should be kept in mind in post fire management of burned areas.

a. Type of grass. Bunchgrasses require lighter utilization rates and longer rest periods than do rhizomatous or annual plant species.

b. Palatable shrubs.

(1) Highly palatable sprouting shrubs often require long rest periods after fire to allow restoration of carbohydrate reserves, to produce seeds, and permit seedling establishment.

(2) Upland shrubs such as sagebrush require bare soil surface and minimal herbaceous competition to enhance reestablishment. Therefore on many of the drier and lower snowfall sites heavy spring grazing could promote sagebrush establishment, if that is the management objective.

c. Riparian communities. Riparian communities with shrubs and trees require long-term rest to recover and light utilization of key shrubs to maintain a healthy community. It may be necessary to fence riparian areas for several years to allow initial recovery.

d. Forb-dominated communities. In order to maintain a forb-dominated plant community, the grasses must receive heavy grazing pressure or be burned more frequently.

6. Economic Factors. The following general guidelines can be used when analyzing fire effects that have an influence on economics.

a. Site selection criteria. The first step is to consider the site potential and set objectives accordingly. These selection criteria can be used for analysis of fire effects on either prescribed burns or wildfire rehabilitation.

(1) Ecological condition. Sites in high-fair or better condition should be selected for prescribed burning if increased herbaceous production of desirable species is a short-term objective and reseeding is not planned.

(2) Presence of desirable species. If improvement of native species is the objective, it must be determined if there are enough desirable remnant plants to make the burn worth conducting. Seeding is very costly and the native species are more adapted to the sites.

(3) Invader species. Are undesirable species or noxious weeds present on the site that might be favored by fire? Species such as cheatgrass, rabbitbrush, and horsebrush are common problems on arid and semiarid rangelands. Any reseeding must be completed before the first growing season to avoid dominance by introduced annual species such as cheatgrass. Noxious weeds may require treatment if there is a significant number present.

(4) Burn size. Is the burn acreage within the management unit large enough to avoid livestock and wildlife concentrations, thus negating the positive fire effects? Refer to Chapter VII.B.3.a. and b., this Guide, for a discussion of the impacts of burn size and configuration on wildlife habitat.

b. Factors to consider in analyzing benefit/cost. The following points are given to consider in planning prescribed burns to improve native herbaceous vegetation. If the objective is to prepare a site for seeding or removing undesirable species, then other principles could be involved.

(1) Conduct burns during the spring period or other seasons that require minimum fire control efforts. The three major costs that can be reduced are equipment, personnel, and fuel break construction. Offsetting factors include ignition problems and objective accomplishment because fuel or soil moisture or weather limit the likelihood of a successful fire.

(2) Burn the largest acreage possible within the constraints of the objectives for the burn. The impact on animal species and other resources will determine the maximum size.

(3) Sites with higher ecological condition and plant vigor respond more quickly and favorably to burning. Greater production increases, a quicker recovery, and better chance for seeding establishment occur when a given ecological site in the mid to upper precipitation zone is burned and less damage to desirable species can be expected.

(4) Extending the life of the fire effects through long-term grazing management can improve the long-term cost effectiveness of a burn project.

E. Summary

Proper site management based on specific objectives and plant species is essential in the management of fire effects. Improper grazing management can easily nullify efforts put into prescription burning or wildfire rehabilitation, as well as impede natural vegetative recovery after wildfire. Impacts of long-term grazing management before and after a fire can be easily overlooked; therefore, proper grazing management including the appropriate kind of livestock, the stocking rate, the season and the intensity of utilization, and the length and frequency of use are most important.

The period of nonuse by livestock necessary after a fire varies considerably with the vegetative composition, site conditions, resource conflicts, and objectives of the burn. Grazing closures apply to prescribed fires and wildfires, whether they are artificially reseeded or recovery is by natural means. In some situations, the only way to ensure nonuse of critical areas after a fire is to construct fences.

Proper grazing management before and after a fire has a major impact on fire effects, vegetation changes, economics, and rehabilitation success. In analyzing fire effects, several site selection criteria should be considered including the site potential, the ecological condition, the presence of desirable and invader plant species, the acreage of burn within the management unit, and the livestock management. The consideration and implementation of these factors determines the benefit/cost ratio and the success of a burn project or postfire rehabilitation effort.

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CHAPTER X - EVALUATION

By Ken Stinson and Melanie Miller

A. Introduction

Documentation is the collection, organization, and storage of all information pertinent to a specific project, in order to maintain a long-term record, and to facilitate project evaluation. Evaluation is both an objective and intuitive process of examining and assessing data and observations to determine if planned objectives were met. Fire effects documentation and evaluation are important in order to replicate positive fire effects and avoid duplication of negative fire effects in future prescribed fires; to assess postfire management of land uses on both wild and prescribed fires; to assess the effectiveness of postfire rehabilitation in preserving site quality; to provide rationale for fire use to the public; to meet legal requirements and liability; to permit evaluation of objectives; and to provide a basis for improvements in project planning, implementation, and management. Fire effects monitoring and evaluation should be included in area monitoring and evaluation plans.

1. Documentation. All documents shall be labeled by project name and number, date, and legal description. A detailed list of types of data that can document a wildland fire are listed in C.3.a., this chapter, pages 3 to 5. The following are general classes of information used to evaluate fire effects, and should be included in project records.

a. A complete description or reference shall be documented for the method and technique used to collect the monitoring data. Monitoring studies appropriate to evaluate land-use objectives should be used.

b. Photographs properly labeled, dated, and filed, including compass direction of photo.

c. Observations before, during, and after a prescribed fire or wildfire.

d. Schedules and responsibility of evaluation and documentation.

2. Organization and Maintenance of Documents. Because fire effects information requires long evaluation periods and the data accumulates over time, it is important that fire monitoring and evaluation records are placed in a permanent file. Records may be needed many years after the original incident to study the site, or for comparison with more recent events on similar sites. The data should be stored in the appropriate permanent project file, such as allotment/ management unit files, or timber sale file. Records should be kept indefinitely or archived and labelled as "Permanent File - Do Not Destroy."

B. Considerations for Fire Effects Evaluation

Evaluation is both an objective and intuitive process of examining and assessing data and observations to determine whether planned objectives were met. There are two aspects of postfire evaluation, evaluation of fire effects, and an evaluation of the effectiveness of postfire management actions. A "cookbook" approach to evaluating fire effects should not and can not be applied in all situations (Pellant 1989).

1. Prescribed Fire versus Wildfire Evaluations.

a. Fire effects. This evaluation provides the decision maker with the necessary information to make sound decisions regarding postfire rehabilitation and management actions.

(1) Prescribed fire. For a prescribed fire, fire effects are evaluated and compared to the fire treatment objectives. The fire treatment is assessed to determine whether it indeed enhanced resource management objectives for the site. Because the event occurs under pre-planned conditions, site-specific prefire and postfire monitoring can occur. If desired effects are not attained, then an evaluation must determine why they were not. If postfire rehabilitation is planned, an assessment must be made whether the fire treatment suitably prepared the site for seeding or planting. A decision is made whether postfire site management objectives that were developed before the prescribed fire are still suitable.

(2) Wildfire. The area in which a wildfire occurs may have established resource objectives, and fire treatment objectives may have been prepared in the Escaped Fire Analysis. However, because wildfires are random events, any prefire monitoring with the specific intent of documenting the effects of that fire can rarely be done. Some monitoring data may be available that was performed for other resource management programs or projects, and some of these data may be suitable for postfire comparisons.

After a wildfire, an assessment is made of the degree to which fire may have affected the ability of the land to meet any resource management objectives that may have been established for the area. In particular, the expected response of the vegetation on the site, and the potential for site erosion, must be evaluated. A plan to take actions paid by Emergency Fire Rehabilitation funds may be written if action is required to mitigate the effects of the wildfire.(1) The decision to use EFR funds is very important; therefore, appropriate personnel should be utilized and the evaluation process should be initiated as soon as possible. Fire effects evaluation can begin long before the fire is declared out. Recommendations are made whether a continuation of present site management practices is acceptable, or if changes are needed, such as in grazing management or use by all terrain vehicles.

b. Effectiveness of postfire actions. An evaluation should be conducted to determine whether postfire site rehabilitation treatments limited negative effects of fire, to assess the impacts of postfire activities such as salvage logging, and to establish the effectiveness of postfire site management actions, such as grazing restrictions, in preserving or improving site quality.

c. Effect of fire and postfire actions on attainment of site objectives. Depending on whether a wildfire or prescribed fire is being evaluated, and the level of land use goals and objectives that existed for the site before the fire occurred, an assessment must be made of whether resource management, fire treatment, and/or rehabilitation objectives were met.

2. Degree of Evaluation. The degree of evaluation that is required depends on:

a. The complexity of the project; several resources may have been monitored and documented.

b. Whether the resource and/or treatment objectives were tied to ecosystem effects or individual species responses.

c. The potential for controversy, involving such factors as designated Wilderness, critical wildlife or watershed values, Areas of Critical Environmental Concern, or political considerations.

d. Experience with or understanding of site specific fire effects, or rehabilitating or managing similar areas.

e. Time and funding availabilities.

f. Availability of existing data bases. Other disciplines may have extensive records, such

as streamflow, weather data, or soils inventories, that can be incorporated into the evaluation.

3. Steps in the Evaluation Process. Existing agency policies and procedures may require certain steps to occur in specific order. The following steps are suggested for postfire evaluation.

a. Identify parties responsible for conducting the evaluation process.

b. Review objectives.

c. Assemble data.

d. Interpret data/observations.

e. Determine if and to what degree objectives were met.

f. Prepare evaluation report, which includes recommendations, for decision maker.

g. Disseminate new findings to colleagues.

h. Observe long-term changes.

C. Evaluation Procedure

1. Identify Parties Responsible for Conducting the Evaluation. An interdisciplinary team approach is used to evaluate both prescribed fires and wildfires. Managers designate both a team and a team leader. All resource specialists involved in planning a prescribed fire or who had the lead in conducting it (Burn Boss or Project Coordinator), should be involved with a prescribed fire evaluation. Any resource specialist involved in the suppression of a wildfire, particularly the Resource Advisor or Environmental Specialist, should be included on the team that assesses the effects of a wildfire. It is very important that individuals with fire effects experience, particularly in similar vegetation types, be involved in the evaluation.

2. Review Objectives. Review any general or specific objectives developed for the site being evaluated. These can include land use decisions, fire planning objectives, resource management objectives, prescribed fire objectives, fire treatment objectives, and rehabilitation objectives. Rehabilitation objectives referred to here are those objectives established as goals for the rehabilitation treatment, such as reducing soil loss, or preventing invasion by exotic plant species. Other objectives that are standard operating procedures are also evaluated, such as keeping a prescribed fire within the prescribed fire target area, meeting safety concerns, protecting cultural resources, and staying within the cost target for the project.

3. Assemble Data.

a. Data sources.

(1) Project file.

(2) Project plan such as Allotment Management Plan, or Timber Sale Plan.

(3) Site specific plan such as Prescribed Burn Plan or Rehabilitation Plan.

(4) Records of any onsite evaluations conducted by Interdisciplinary teams, such as preparation for a prescribed fire, or observations made during or shortly after a wildfire.

(5) Any reports associated with the occurrence of a wildfire being evaluated, such as the Escaped Fire Situation Analysis, Burned Area Report, or reports by the Fire Behavior Analyst, Incident Commander, or Resource Advisor.

(6) Fire effects data or evaluations from similar projects, such as other prescribed fire or wildfire evaluations.

(7) Climatological data.

(a) National Oceanographic and Atmospheric Administration (NOAA), e.g., monthly summaries.

(b) Remote Automated Weather Stations (RAWS), including archived

data.

(c) Local manual weather stations.

(d) State climatologist.

(e) Soil Conservation Service (SCS), e.g., snow surveys and soil moisture indices.

(8) Weather, fuel, or soil moisture data collected at the time of the fire.

(9) Air quality permits, smoke observations, or data collected at the time of the fire.

(10) Any site specific monitoring information, such as preburn and postburn fuel, soil, vegetation, or fuels data. For a wildfire, some information on prefire vegetation composition may be obtained from any resource management or activity plan for the area, or from rangeland inventory, trend, and utilization studies.

(11) Aerial photographs.

(12) Resource maps, such as vegetation, soil, timber, or cultural site locations.

(13) Records that document uses of the area.

(a) Timber sales, regeneration surveys, and records of post-logging treatment, such as slashburning, pile burning, scarification, or no treatment.

(b) Actual use and utilization, and season of use by licensed livestock or wild horses; utilization levels on key species; unauthorized use records (trespass file).

(c) "On-the-ground" observations, such as extensive amounts of wildlife use during a particular period of time.

(d) Use by other public land users, such as sportsmen or conservation groups, fish and game agencies.

(e) Observations on extreme weather events, anomalous climatic trends, grasshopper or rodent infestations, wildlife use, and ORV impacts.

b. Data adequacy. Compare the amount of monitoring data collected with the amount planned for collection. If data collection was inadequate, determine the reasons why planned monitoring was not carried out.

c. Statistical analysis. Determine if the appropriate statistical analyses have been completed, or if inadequate data were collected to conduct the analysis. (See Data Analysis.) If data were collected in such a fashion that statistical analysis is not possible, or is inadequate, note should be taken so future data are properly gathered.

4. Interpretation of Data/Observations.

a. Uncertainty and reliability. Fiscal and time constraints do not allow for collecting enough data for managers to make risk-free decisions, and some uncertainty will remain, even if a statistical analysis is conducted. Decide what risk level to accept, and whether any data inadequacy is the result of uncontrollable factors such as acts of nature (floods, hailstorms), vandalism, or equipment failures. If poor study design prevents proper data analysis, document this fact. Be sure the decision maker is informed of the reliability of data; i.e., distinguish between use of complete and properly collected data (hard data) and assumptions made where data gaps exist (soft data).

b. Results of data analysis. Explain data analysis results in terms that non-statisticians can understand. Integrate any quantitative or qualitative, onsite data with observations and results from other studies. Be wary of interpreting data mechanically without considering the possibilities of undocumented causes for change. If necessary, use expertise from other offices to decipher complex interrelationships. Prepare a summary report of the findings. **5. Determine If and To What Degree Objectives Were Accomplished.**

a. Indicate whether each planned objective was met and to what degree it was accomplished.

b. If objectives were not met, identify reasons why. Some general areas to consider are:

(1) Objectives were unattainable or mutually exclusive.

(2) Timeframes for objective accomplishment were unrealistic.

(3) Operational procedures used to implement the project were not appropriate, such as an ignition method or ignition pattern that caused a more severe treatment than needed to produce the desired fire effects.

(4) The operational plan and/or procedures outlined in the project plan were not followed.

(5) Followup site management was inadequate; e.g., postfire grazing occurred too quickly or at too high an intensity, or off road vehicle use occurred on a burned area before vegetative recovery could sustain ORV use.

(6) Monitoring techniques or sampling intensity were not adequate to detect change.

6. Prepare Evaluation Report with Summary and

Recommendations.

a. Prescribed fire.

(1) Brief summary of actions taken and burning conditions.

(a) Date, time of day fire occurred, acreage burned, and ignition pattern and method.

(b) Weather, fuel, and soil moisture conditions during the fire.

(c) Observed fire behavior and characteristics.

(d) Observed smoke production and characteristics.

(e) Any differences between fire prescription and actual burning conditions.

(f) Map of the proposed fire area and the area that actually burned.

(2) List of objectives of prescribed fire.

(3) Summary of monitoring results and observations.

(4) Describe which and to what degree objectives were met (expected results versus actual results).

(5) If objectives were not met, briefly describe those factors that were responsible for the lack of achievement.

(6) Make recommendations to management.

(a) Immediate changes needed in management strategies.

(b) Changes in how future prescribed fires could be planned or implemented, including changes in prescription or ignition that would lead to better results.

(c) Changes in postfire site management.

(d) Changes in monitoring procedures.

(7) After management review and decision(s), evaluation report should be filed in the appropriate file(s) and required followup actions assigned and initiated. This report should be signed and dated by the preparer and the reviewing official.

(8) Followup on management decision(s) - repeat evaluation process.

b. Wildfire - fire effects evaluation.

(1) Brief summary of wildfire extent and effects.

(a) Date and acreage of public lands burned.

(b) Prefire vegetation.

(c) Map of the burned area including soil mapping units.

(d) Multiple-use objectives identified in land use plan, e.g., watershed value, wildlife habitat, livestock forage.

(e) Interdisciplinary team findings.

i. Estimated percent survival of key plant species.

ii. Potential for postfire erosion and sedimentation.

iii. Potential for invasion of site by exotic species.

(2) Recommendation for postfire actions.

(a) Postfire rehabilitation actions, e.g.,

i. Seeding, including recommended species and seeding rates.

ii. Contour falling of trees.

iii. Construction of instream structures to control channel erosion.

(b) Feasibility of conducting salvage logging.

i. Locations within burned area.

ii. Methods that will not cause negative impacts on soil.

(c) Changes in postfire land uses, e.g.,

i. Temporary restriction or exclusion of grazing to allow recovery of perennial plants or establishment of seeded or planted vegetation.

ii. Road or all terrain vehicle closures.

(d) Need for fence construction to exclude livestock and/or wildlife.

(3) Specific objectives for postfire management: specify desired condition, e.g.,

(a) Limit erosion to a specified amount.

(b) Restore site to a productive state by salvaging merchantable timber and replanting trees, and leaving a specified number of wildlife trees that do not pose a safety hazard.

(c) Obtain a specific level of plant cover or productivity.

c. Wildfire - rehabilitation and/or management evaluation.

(1) Prepare a brief summary of actions taken.

(a) List management objectives and planned actions.

(b) Describe actions taken and date.

(c) Include a map of treated or rested areas.

(2) Summary of monitoring results and observations.

(3) Describe which and to what degree objectives were met.

(4) If objectives were not met, briefly summarize what factors were the cause for lack of achievement.

(5) Make recommendations to management.

(a) Immediate changes required in management strategies.

(b) Recommendations for improvement in rehabilitation and postfire site management practices.

d. Post evaluation actions.

(1) After management review and decision(s), the evaluation report should be filed in the appropriate file(s) and the required followup actions assigned and initiated. This report should be signed and dated by the preparer and the reviewing official.

(2) Followup on management decision(s) - repeat evaluation process if appropriate.

(3) If no management action was taken (e.g., the burned area was grazed, or no erosion control efforts were made), document any adverse impacts that occurred and what future management actions need to be taken under similar conditions.

7. Disseminate New Findings To Other Interested Parties.

a. Fire Effects Information System.

b. Internal or interagency newsletters.

c. Professional meetings.

d. Local, state or regional workshops.

e. Agency technical publications.

f. "Expert Systems" or relational databases.

g. Office-to-office memos.

h. Professional journals.

i. Videos and other visual media.

j. Electronic bulletin boards.

8. Observe Long-Term Changes.

a. Within what timeframe did the original target species reestablish?

b. Are noxious weeds or unwanted species increasing in the postfire environment?

c. Have cyclic climatic events, such as drought or a series of wet years, affected postfire vegetative recovery? What effect have they had on plant community composition and characteristics?

d. Are postfire management actions still having the desired effects?

e. Is the level or type of postfire management adversely affecting desirable native vegetation or seeded species?

f. How have the different species that were originally seeded persisted?

g. Is cumulative acreage burned by wildfires large enough to affect whether future prescribed burns should be carried out?

D. Summary

Evaluation of both monitoring data and the impacts of postfire activities must be conducted in order to ensure that lands receive the best possible fire treatment, rehabilitation, and postfire management. Once we have monitored and evaluated enough projects and management actions on similar sites, and adjusted our actions based on these results, we can become more confident that the proper treatment is being implemented. The same degree of monitoring and evaluation need not be carried out on all subsequently treated areas if vegetation type, soil type, and treatment prescription are similar to that of other successful treatments. However, it is professionally unacceptable to conduct no prefire or postfire monitoring or site observation, to assume that an area is ready for grazing because the designated length of time has passed since the occurrence of a prescribed or wildfire, or to conduct no evaluation of the implementation or effectiveness of postfire site management in preserving or enhancing site quality. Without some check on the results of our activities, accumulated assumptions can lead to land treatments that do not meet resource management goals and objectives, and lead to deterioration, instead of enhancement, of site quality.

1. See BLM Manual Handbook H-1742-1 (USDI-BLM 1985b) for a discussion of EFR planning procedures on BLM land.

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CHAPTER XI - DATA MANAGEMENT

By Dr. Robert Clark

A. Introduction

Managers can gain a number of benefits from the analysis of their data. The results of the analysis helps managers make informed decisions leading to favorable outcomes. Analyzing and manipulating the data gives the manager a special familiarity with the data and a feel for how precise and repeatable the sampling is likely to be. Describing and defending the credibility of the data is easier when it has been appropriately analyzed and described in standard statistical terms. Practice and familiarity with the most common statistical analyses provides a basis for better understanding, interpretation, and proper application of results presented in professional fire literature.

This chapter will acquaint fire managers with some elementary statistical methods that can be used to help make decisions. The methods are demonstrated by example. Managers interested in more detailed discussion or more sophisticated methods are referred to Freese (1962, 1967), Little and Hills (1978), and Eshelman et al. (1986). Managers are also encouraged to contact a statistician ***before*** data are collected to ensure the data will be usable and appropriate, and that assumptions of analysis are not violated.

Statistical terms used in this chapter are included in the Glossary of this Guide. Additional discussion is available in statistics texts.

B. Principles and Procedures of Data Analysis

1. Determination of Sample Size (Number of Observations).

Samples (observations) cost money, but so do decisions based on inadequate data. Therefore, it is helpful to collect an appropriate number of observations. One useful method to determine the appropriate sample size for continuous data is (Freese 1967, p. 12):

$$n = (t^2 s^2) / E^2$$

where:

n = the required number of observations.
t = tabulated Student's t available in most statistics texts.
s = sample standard deviation (and s^2 = sample variance). Note the unfortunate situation here, that some estimate of variance is required to calculate sample size, i.e., there is one equation with several unknown values. This is usually handled by collecting a preliminary sample from which to estimate a variance and a mean, which in turn are used to calculate the sample size.
E = desired precision, expressed as a proportion of the sample mean.

Example: Suppose the manager needed to know the foliar moisture content of basin big sagebrush on a proposed prescribed fire area. Because fire behavior in sagebrush is closely related to foliage moisture content, the manager decided to sample such that the moisture content was estimated within 10 points of the true moisture content level at the 90 percent confidence level. This indicated that the manager wanted to know the moisture content on the site within plus or minus 10 points of the true average value (precision level), and wanted the estimate to be correct 9 out of 10 times (confidence level). 10 points of error was selected because fire behavior in sagebrush can begin to change quite significantly over a range of 20 percent foliar moisture content (plus or minus 10 percent).

The manager collected foliage from 12 different plants, dried and weighed the samples, calculated the moisture content, and recorded the following results. What sample size is required to meet the manager's needs? Was the preliminary sample adequate?

plant	x = moisture content (%)	x^2

1	70	4900
2	90	8100
3	80	6400
4	70	4900
5	60	3600
6	80	6400
7	90	8100
8	100	10000
9	90	8100
10	80	6400
11	70	4900
12	60	3600
n = 12	$\hat{E}x = 940$	$\hat{E}\, x^2 = 75,400$

Note that the Ê symbol means summation.

a. Step 1. Look up t value from t table in most statistical texts (e.g., Freese 1967, p. 77). Degrees of freedom (df) are n - 1 (12 - 1 = 11). The appropriate t value at the 90 percent confidence level (or 10 percent error rate) is 1.796.

b. Step 2. Calculate the variance (s^2) of the preliminary, 12-observation sample according to [note that this calculation results in the sample variance (s^2) rather than the sample standard deviation (s)]:

$$S^2 = \hat{E}x^2 - ((\hat{E}x)^2/n) / n-1 = 75,400 - ((940)^2 / n) / 11 = 160.6$$

c. Step 3. Decide how much error can be tolerated. In this example, the manager wanted the estimate to be within 10 percentage points of the true mean moisture content. Therefore, E = 10.

d. Step 4. Calculate the appropriate sample size according to the formula described above:

$$n = (t^2\, s^2) / E^2 = (1.796)^2\, (160.6) / (10)^2 = 5.18 = 6 \text{ observations}$$

e. Conclusion. The preliminary sample of 12 observations was adequate. If the preliminary sample of 12 observations had been inadequate, the manager had several options. First, more observations could have been taken. Second, the acceptable precision level could have been lowered. Third, a lower confidence level could have been accepted and some added risk incurred. Or fourth, the fire prescription might have been altered (e.g., faster windspeed or lower fuel moisture content) to compensate for the added uncertainty. The important point is that the manager had some quantitative information on which to base a decision.

f. Note. The size of the preliminary sample depends on the variable being measured, on the objective for measuring the variable, and on funds, time, and work force constraints. Inherent variability associated with most natural resource sampling indicates that 10 or more observations may usually be required to obtain a reasonable estimate of variance. One observation is **never** adequate because degrees of freedom would be zero and no analysis is possible.

2. t-Test for Paired Observations (Plots). This test is especially useful for comparing effects between two fire treatments, such as burned vs. unburned, or backing fires vs. heading fires. An assumption of the test is that pairs of plots are established prior to the treatment, each group has the same population variance, the population of observations follows the normal distribution, and that treatments are randomly assigned to each individual plot. It is possible, however, to establish plot pairs adjacent to firelines (one plot on either side) such that these assumptions are not violated. A similar test for unpaired plots (Freese 1967, p. 24) should be used where plots are not paired; that test, however, is slightly more time consuming and a slightly greater loss of sensitivity may occur. Only the t-test for paired plots is illustrated here.

Example: A fire manager suspected that fire residence time might be an important factor affecting postburn Idaho fescue *(Festuca idahoensis)* production. The manager designed an experiment to evaluate the suspicion. An area was selected where part of the burning would be done by a backing fire and part by a heading fire. A series of 10 plots were clipped, oven-dried, and weighed preburn to establish that the two areas were from the same population and had similar variances, and to determine preburn fuel loading. The heading and backing fires were then conducted on the same day under similar environmental conditions.

Sufficient rate of spread and flame depth measurements were made during the fires to establish that residence time was significantly ($p = 0.05$) different between the two treatments. One year later the fire manager clipped, oven-dried, and weighed Idaho fescue standing crop to compare "production" on the two treatments. Based on the following results, and assuming that residence time (and its implications) was the only difference between the heading and backing fires, does residence time influence postburn production?

Quadrat	Heading	Backing	d = Heading - Backing	d^2
1	22	24	-2	4
2	15	13	+2	4
3	19	19	0	0
4	19	12	+7	49
5	21	17	+4	16
6	20	17	+3	9
7	18	19	19	1
8	20	12	12	64
9	21	15	15	36
10	14	14	14	0
n = 10	$\hat{E}_h$=189	$\hat{E}_b$=162	$\hat{E}_d$=27	$\hat{E}_d{}^2$=183

$x_h = 18.9$ $x_b = 16.2$

a. Step 1. Note that by inspection the two means appear to be different (18.9 appears greater than 16.2). The null hypothesis, H_o, is that the two means are equal, i.e., x_h is equal to x_b. The alternate hypothesis, H_a, is set up to allow rejection, i.e., x_h is not equal to x_b. This hypothesis will result in a "two-tailed" test; one-tailed tests also can be established by setting the means in the hypotheses "greater than" or "less than" rather than "not equal to." Note that one-tailed tests require different t values than two-tailed tests.

b. Step 2. Establish the confidence level for testing. By convention, testing in this example was set at the alpha = 0.05 level (this is the same as the 95 percent confidence level, or that the acceptable risk is to be wrong one chance in 20 due to chance alone). From the t table, with n-1 degrees of freedom and an error rate of 0.05, t = 2.262. This is the tabulated value below which the difference between sample means is likely to be due to chance alone. A calculated value larger than 2.262 would suggest that a real difference exists between the two means, and on the average, this conclusion would be correct 19 of 20 times.

c. Step 3. Calculate the variance of the difference between sample means according to:

$$s_d^2 = \hat{E}d^2 - (\hat{E}(d)^2 / n^{)\,/} n - 1 = 183 - ((27)^2/10) / 9 = 12.2333$$

d. Step 4. Calculate t according to:

$$t = (x_h - x_b) / \S[s_d^2 / n] = (18.9 - 16.2) / \S[12.2333 / 10] = 2.4412$$

§ = square root

e. Conclusion. The calculated value of 2.4412 is larger than the tabulated t value of 2.262. This suggests that a real difference exists between the two means. The fire manager may report to the supervisor that postburn Idaho fescue production was different ($p = 0.05$) between the heading fire and backing fire sites, and that more production occurred on the sites burned with a headfire. If it is certain that the **only** difference between treatments is residence time, it is also reasonable to assume that long residence time was more detrimental than short residence time. This conclusion is likely to be correct 19 out of 20 times. Note that this statistical significance does not necessarily imply biological significance. Also note that this "study" was not replicated, nor was a "control" treatment used; both are strongly encouraged. Also note that the method and level of testing, and the hypothesis, were established before any sampling or burning occurred.

3. Chi-Square Analysis of Counts. Chi-square is a nonparametric method that is useful for analyzing binary enumeration data that fall into two categories, such as scorched or not scorched, alive or dead, scarred or unscarred, or sprouted or not sprouted. These types of data are common in fire management. Although several procedures are available, the following example illustrates a useful method for many fire management data.

Example: One half of a plant community containing bitterbrush *(Purshia tridentata)* plants was burned in the fall and the other half was burned in the spring. The fire manager tagged 20 randomly located bitterbrush plants in each area, before burning, to estimate mortality. One year after burning, the fire manager found 11 tagged plants alive on the spring burned site and eight tagged plants alive on the fall burned site. At the 90 percent confidence level, was there a differential response between fall and spring burned plants?

a. Step 1. Set up a 2 x 2 contingency table (2 rows and 2 columns of observations):

	Spring	Fall	Total
Alive	11	8	19
Dead	9	12	21
Total	20	20	40

b. Step 2. Calculate chi-square. The general procedure, based on a 2 x 2 contingency table, is:

	I	II	Total
1	a	b	a+b
2	c	d	c+d
Total	a+c	b+d	a+b+c+d

$\text{chi-square} = ([(| ad - bc |) - 1/2\, n]^2\, n) / (a + c) (b + d) (a + b) (c + d)$

$\text{chi-square} = \underline{[(|(11 \times 12) - (9 \times 8)| - 1/2\, (40)]^2\, (40))} / (20) (20) (19) (21)$
$= 0.4010$

Note that the vertical bar (|) indicates absolute value, so it is irrelevant which cross-multiplication product is subtracted from the other (i.e., 11 x 12 - 9 x 8, or 9 x 8 - 11 x 12). Use of the Yates Correction, [- 1/2 (n)] and [1/2(40)] found in the numerators of the above equations, decreases the chi-square value, and thus reduces the chance of declaring a significant difference when one does not exist.

c. Step 3. Look up the tabular value for chi-square in a chi-square table, such as Freese (1967, p. 82). Values in a chi-square table are different than those in a t-table, and a t-table should never be used to obtain values for a chi-square test. Degrees of freedom (df) for the 2 x 2 contingency table are calculated according to: [(rows - 1) x (columns - 1)]. In this example, df = (2-1)(2-1) = 1. Since the fire manager decided to test at the 90 percent confidence level (10 percent error level), the appropriate chi-square value to test this example is 2.71.

d. Conclusion. Since all values below 2.71 are below the 10 percent error threshold, the calculated value of 0.4010 is not significant. The manager concluded that, in this example, the sprouting of bitterbrush was not different between spring and fall fire treatments. Note that no cause and effect was implied. If a statistically significant difference had been observed, the difference could have been due to environmental factors or other unknown causes. This point is especially important for data gathered during different time periods.

4. Other Tests. Two additional statistical testing methods that are beyond the scope of this Guide but may be useful in routine fire management work include analysis of variance (often abbreviated AOV or ANOVA), and linear correlation and regression.

a. **Analysis of variance.** ANOVA is a method used to separate sources of variation *within* treatments and *among* treatments and may be used with several different experimental designs such as the completely randomized design or the randomized complete block design. ANOVA produces an "F" test of significance, and is often used with several mean separation tests, such as Duncan's New Multiple Range Test, or Orthogonal Comparisons. Although ANOVA has many potential applications in fire management, a statistician should be consulted before its use. Several texts, for example, Little and Hills (1978), provide excellent discussions of ANOVA.

b. Linear correlation and regression. Linear correlation and regression analysis are mathematical methods used to describe how independent variables relate to each other, and how dependent variables relate to independent variables. These approaches to describing and understanding relationships common in fire management work **do not** imply any cause and effect; they merely describe associations and relationships. Because the potential for misuse is so great, many statisticians discourage their use by apprentices. They are especially useful, however, when used with the aid of a reputable statistician.

5. Crunching Numbers. Development of microchip technology has made the manipulation of large data sets rapid and easy for fire managers. The three simple tests (sample size, t-test, and chi-square) that are described above can all be easily calculated on simple, 4-function, hand held calculators. Many small, hand held calculators are commercially available that have internal, preprogrammed statistical functions that quickly calculate the sample mean, variance, and sometimes, even complete linear regression. One caution is that the user should be aware whether the calculator in question uses n or n - 1 for degrees of freedom in the variance and standard deviation, and should understand the implications.

The Hewlett-Packard HP-71B hand held calculator, which is routinely used for fire behavior calculations, has several Custom Read Only Memory (CROM) modules available. One CROM (American Micro Products, Inc. 1984) contains many parametric and nonparametric tests and is powerful enough to handle relatively large data sets. Such devices make statistical analyses of fire management data routine.

Many statistical packages have been developed and are available for micro and mini-computers (e.g., StatSoft, Inc. 1987). Some packages include graphics capability, and many are available for several hundred dollars or less. Fire managers who anticipate the collection of large amounts of data for statistical manipulation are encouraged to investigate statistical packages that are available.

Mainframe statistical packages (Dixon 1985, SAS Institute Inc. 1985) are designed to handle very large data sets and complete an enormous number of statistical tests. These large machines are usually restricted to research institutions; however, fire managers should be aware that most colleges, universities, and experiment stations have access to mainframe computers. The use of such machines might be cost effective if used only when infrequent but large data sets must be manipulated.

C. Resource Management Considerations

1. It is essential to know what the questions are before sampling and data analysis can be designed to obtain answers. Sampling and data analysis must be objective driven. Further, objectives should be developed with sampling and data analysis in mind so that the objectives are reasonable, measurable, and lend themselves to analysis.

2. Sampling design and intensity (number of observations) should be determined **before** initiating any data collection to ensure sampling and analysis procedures are appropriate. The number of required observations depends on desired precision and confidence levels; for most management purposes it is usually adequate to sample within 20 percent of the mean at the 80 percent confidence level.

3. Experienced statisticians should be consulted **before** data are collected and **after** data are analyzed.

4. It is not necessary, nor feasible in most cases, to sample and analyze data from every community on every wild or prescribed fire. Usually it is better to do an adequate job on one community than an inadequate job on two or more communities. Further, it is often possible to design a series of prescribed fires with a sampling and data analysis scheme such that one fire or one stratum is emphasized and the remainder are spot checked. Biologically oriented statisticians can provide advice on how best to sample and analyze data when time and funding are constrained.

5. Inadequate sampling is often more expensive than excessive sampling; optimum sampling is usually the most cost effective.

6. Replicates are necessary to determine "sample error," and untreated "controls" are necessary to isolate fire effects from other effects.

7. After data are collected and analyzed, consider both statistical significance and biological significance; it is possible to establish statistical significance that has no biological significance.

8. Place measured trust in results of data analysis. An unexpected or undesired result is not a valid reason for discarding results and "massaging" the data. Data analysis should be used to enhance understanding as well as provide support.

9. It is tempting to draw inappropriate conclusions from analyzed data. Caution is advised.

D. Methods to Monitor Fire Effects

1. The appropriate sample size for each data set should be determined using the method described in B.1, or another statistically acceptable method. A more detailed description of this method to determine proper sample size is given in Norum and Miller (1984).

2. The t-test described in B.2 is especially useful for comparing the means of several treatments, such as burned vs. unburned, or fall burned vs. spring burned. Means that are helpful to compare include "production," cover, and density. The test assumes that identical treatments were applied; therefore, the comparison of spring burned vs. fall burned treatments should be approached with caution.

3. Chi-square is a nonparametric test that is especially useful for analyzing counts of binary data; such data fall into two convenient categories, such as alive or dead, or sprouted or not sprouted.

4. A statistician should be consulted for additional data analysis methods. Biometricians and statisticians who can provide assistance may be located at agency offices, national and regional service centers such as the BLM Service Center at Denver, experiment stations and universities.

E. Summary

Statistical analysis of data and interpretation of results are helpful for understanding fire effects and provide an essential tool for the decision making process. Calculation of the appropriate sample size is essential, and is based on desired precision and confidence levels. The t-test for paired plots, and chi-square analysis of counts, are particularly useful for understanding fire effects. Other, more sophisticated techniques may require assistance of a statistician.

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CHAPTER XII - COMPUTER SOFTWARE

By Melanie Miller

A. Introduction

Many packaged computer programs have been developed that can provide information useful for managing or interpreting fire effects. Some programs are accessible on mainframe computers, while others are available on floppy disks that can be loaded onto personal computers. Additional information about programs described here can be obtained by reading the referenced publications, or contacting specific offices, where indicated.

B. Weather Analysis

Weather records can be used to manage fire effects by helping to establish seasons and parameters for appropriate fire prescriptions, and to document prefire weather trends and weather conditions at the time of the fire. Records of postfire weather can be used to make inferences about causes for observed fire effects. Long-term records are required to establish a statistical basis for occurrence of seasonal trends in elements such as temperature or rainfall, to detect deviations from seasonal trends, or to document the likelihood of occurrence of specific sets of weather conditions, such as combinations of temperature and relative humidity.

1. Computerized Databases. Sources for data on which computerized searches and analyses can be performed are the network of Remote Automated Weather Stations, and the National Interagency Fire Management Integrated Database.

a. Remote Automated Weather Stations (RAWS). The Remote Automated Weather Station (RAWS) System is a program that provides current remotely sensed weather data from stations established on Federally administered lands (German 1988). The RAWS network contains about 350 weather stations on BLM lands in the lower 48 States, as well as about 250 weather stations established on other agency lands. There are approximately 40 RAWS stations in Alaska. Over the next 5 years, approximately 60 to 100 additional RAWS stations will be established.

The RAWS system uses self-contained meteorological collection platforms and a mini-computer controlled satellite receiving station located at the National Interagency Fire Center (NIFC). The weather stations collect weather data, summarize it on an hourly basis, and then transmit data on a one hour or three hour basis to NIFC through the GOES satellite system. A computer at NIFC immediately distributes the weather data to all users on the Initial Attack Management System (IAMS), to the Weather Information Management System (WIMS) (see item 1.b. below), and to the National Weather Service. BLM users access this "real-time" weather data through the IAMS computer located in most BLM District Fire Management offices. Other agency users acquire data through WIMS.

NIFC archives all weather data for permanent storage. A copy of this archived information is distributed quarterly and annually to the Desert Research Institute at the University of Nevada at Reno. Weather information can be obtained in a quarterly summary report for each station, and through specially requested reports and studies. BLM users request these reports and studies from BLM staff at NIFC, while other agency users obtain these data from the Desert Research Institute.

b. National Interagency Fire Management Integrated Database (NIFMID). The National Interagency Fire Management Integrated Database contains the historic fire weather information previously contained in the obsolete National Fire Weather Data Library. It is located at the National Computer Center - Kansas City (NCC-KC), managed by the U.S. Department of Agriculture. The library contains daily observations from all fire weather stations, collected at the time of peak burning conditions (1300 hours, local standard time) throughout the fire season. The Weather Information Management System database (WIMS), a replacement for AFFIRMS, stores the1300-hour observations from automated and manual fire weather stations, as well as 60 days of 24-hour observations from RAWS stations. The long-term historical weather database of NIFMID stores 1300-hour observations.

Access to NIFMID is available through computer software packages that reside in the computer library at the Kansas City Computer Center. In order to use these programs, users must establish an account. Once an account is opened, all access information is provided to the user. Telecom- munications packages on most computers can be used to communicate with this USDA computer. See item 2. Computer Programs, for descriptions of computer programs available through NCC-KC.

2. Computer Programs.

a. KCFAST. KCFAST is a program that facilitates use of data stored in NIFMID. KCFAST is a utility that assists the casual user of this database by removing the need to remember all of the commands required to extract and format weather data stored for a particular weather station. KCFAST itself does not perform analyses on data sets from the fire weather data library, but it makes it easy to transmit these data to a personal computer, where weather analysis can be performed. It facilitates operation of the other programs described in this section, as well as other software such as that used for fire planning. KCFAST is available in versions that operate on the U. S. Forest Service Data General system, as well as IBM compatible personal computers. To use the PC version, communication software is required that can transmit an ASCII file to a remote computer and log screen activity to a PC file (Bradshaw and Andrews 1990).

b. FIREFAMILY. Three different computer programs were consolidated into FIREFAMILY: FIRDAT, SEASON, and FIRINF. These programs use historic weather data to predict future fire management needs, and integrate fire management with other land management activities. The weather data used is that stored in the NIFMID (1.b., above), and FIREFAMILY software is on the USDA Kansas City computer. These programs are fully described in the publication by Main et al. (1988).

(1) FIRDAT. FIRDAT can combine up to 100 years of historical weather records with National Fire Danger Rating System (NFDRS) equations to produce frequency distributions and graphs of NFDRS indices and components. This can include the NFDRS calculated fuel moisture. FIRDAT can also produce lists of daily weather observations.

(2) SEASON. SEASON uses FIRDAT data to summarize variations in NFDRS inputs and fire danger severity during a fire season, and seasonal patterns of fire danger over many years. Fuel moisture values, fire danger indices, or fire behavior components can be presented in tabular and graphic form.

(3) FIRINF. FIRINF allows the analysis of the co-occurrence of any two NFDRS indices over 10-year periods.

c. PCFIRDAT. PCFIRDAT is a version of FIRDAT that has been rewritten for use on IBM compatible computers. Using the PC version of KCFAST, data are transferred from the NIFMID to a personal computer, and PCFIRDAT is then used to perform data analyses. PCFIRDAT, as well as PC versions of SEASON and FIRINF are in the final stages of development. Work is being performed by the California Department of Forestry.

d. PRESCRB. This program provides a climatological summary of specific fire weather occurrences. The program counts the occurrences of days on which all variables specified in a prescription are met, and gives the probable number of days in any year on which the prescribed conditions specified are likely to occur. The average number of days of occurrence of prescribed conditions during successive 10-day periods of the year is given. The average number of days in each burning period also can be obtained, giving the prescribed fire planner an idea of whether days meeting prescribed conditions are likely to occur singly, or in a series. Furman (1979) documents use of the PRESCRB program. An advantage of this program is that it can use weather data from other sources than NIFMID.

e. RXWTHR. RXWTHR (Prescribed Fire Weather) provides climatological summaries and co-occurrence frequencies of user selected fire weather and fire danger rating parameters (Bradshaw and Fischer 1981a, 1981b). The data base is the computerized fire weather records within NIFMD. Simultaneous occurrence of two or three of fifteen prescription parameters can be summarized, and shown in tables. For example, tables can include summaries of temperatures, two way co-occurrence tables for wind direction and wind speed, and three way co-occurrence tables for temperature, relative humidity, and wind speed. Once a user has obtained a feeling for the general pattern of occurrence of desired prescribed conditions, screening out those that have a low probability of occurring simultaneously, a more detailed analysis can be conducted using RXBURN. Please note that a sixteenth prescription parameter available for analysis in the program is duff moisture. This value is based upon a duff moisture model that was offered on an experimental basis in RXWTHR and RXBURN. This model does not provide accurate results, and the duff moisture output produced by these two programs should not be used.

f. RXBURN. RXBURN (Prescribed Fire Conditions) provides an analysis of the frequency of occurrence of a set of prescription conditions, also using the NIFMID as a database. Up to 15 parameters can be used in a single prescription. Users define a preferable range of prescribed conditions, and a broader range of conditions that is still acceptable. Output tables include a summary table of the percentage of weather conditions that are preferable, acceptable, and unacceptable; a table that shows frequency of occurrence of preferable, acceptable, and unacceptable conditions in each successive 10-day period, and by month; the number of successive days that prescribed conditions have occurred in each 10-day period and each month; and the probability of meeting the prescription 1, 2, and 3 days in the future for each month. As discussed under 2.d., RXWTHR, the duff moisture model that provides a basis for parameter 16 is inaccurate; this parameter should not be used.

There are two limitations to the use of RXWTHR and RXBURN. Weather observations are rarely recorded for more than the five months of the year that are the normal "fire season," and many prescribed fires are staged before and after this period. The single observation per day that must represent the entire day's weather is taken during average worst case conditions, 1300 hours (Standard Time), southwest aspect, midslope, and open canopy. This may poorly represent the weather at the time of the day when a prescribed fire would be implemented.

g. Other. An additional set of climatological software is described by Bradshaw and Fischer (1984). Eight computer programs for extensive climatic summaries of weather variables, temperature, relative humidity, wind, and precipitation, records are available. Five basic climatology programs analyze NIFMID records by 10-day periods and by month. Three averaging programs adjust results from the climatology programs to smooth variances caused either by short periods of record or incomplete station data.

C. Fire Behavior

1. BEHAVE. BEHAVE is a set of interactive, user friendly computer programs that are used for estimating behavior of wild and prescribed fires. BEHAVE is an integral part of the Fire Behavior Prediction System that is used by Fire Behavior Analysts to estimate fire potential under various fuels, weather, and topographic situations (Burgan and Rothermel 1984). BEHAVE predicts the behavior of a steady state fire advancing in surface fuels along a front. It cannot be used to estimate long-term fuel burnout, non-flaming combustion, or extreme fire behavior. The BEHAVE system consists of two subsystems: BURN and FUEL.

a. FUEL subsystem. The FUEL subsystem has two programs: NEWMDL and TSTMDL (Burgan and Rothermel 1984). NEWMDL ("NEW MODEL") is used to construct fuel models for specific application when the existing 13 stylized fuel models in the Fire Behavior Prediction System do not adequately describe fuels at a particular location. TSTMDL ("TEST MODEL") is used to test the fuel models developed in NEWMDL. The FUEL subsystem is rarely used except by trained Fire Behavior Analysts or for research purposes. Please note that these fuel models are not the same as those used in the National Fire Danger Rating System.

b. BURN subsystem. The BURN subsystem is frequently used on wild and prescribed fires. This subsystem has three components, FIRE 1, FIRE 2, and RXWINDOW (see section C.2.). FIRE 1 contains the wildland fire behavior prediction model developed by Rothermel (1972). It includes modules that allow prediction of fire behavior (DIRECT and SITE), fire growth (SIZE), containment requirements (CONTAIN), and spotting distance (SPOT). Fire effects on the tree overstory are predicted in SCORCH and MORTALITY, described in sections D.1.a., and D.1.b., this chapter. FIRE 2 allows calculation of fine dead fuel moisture (MOISTURE), the probability of ignition (IGNITE), and relative humidity (RH). Contents and operation of the BURN Subsystem are described in Andrews (1986) and Andrews and Chase (1989). Users require training for optimum application of this software to wildland fire situations.

2. RXWINDOW. RXWINDOW, a component of the BURN subsystem in BEHAVE, essentially runs DIRECT backwards, enabling prescribed fire planners to obtain detailed windows of required fuel moisture and wind conditions based upon desired fire behavior (Andrews and Bradshaw 1990). Desired fire behavior such as flame length or rate of fire spread are entered, and the program calculates which combinations of fuel and weather parameters would result in the fire behavior specified. The program uses one of the 13 standard fire behavior fuel models, or a custom model developed in the FUEL Subsystem. Other input values include slope of the burn area and exposure of fuels to the wind. The user can optionally set limits on 1-hour, 10-hour, 100-hour, live woody, and live herbaceous moisture content, and effective windspeed.

a. FIRE. The FIRE module generates tables that display combinations of effective windspeed and weighted fuel moisture that result in the desired fire behavior. It indicates those pairs of wind and dead fuel moisture that yield a fire within the fire behavior prescription. For those fuel models where live fuel moisture is a component, the program prints ranges of live fuel moisture for each appropriate wind and dead fuel moisture pair.
b. WIND. The WIND module requires input of site description parameters, and whether the prescribed fire will be a headfire, backfire, or flanking fire. Based on a constant slope, the program prints a table of 20-foot windspeeds coming from different directions with respect to slope that will produce a range of effective windspeeds. WIND can use either effective windspeeds identified in the FIRE output table or windspeeds selected by the user.

c. MOISTURE. The MOISTURE module of RXWINDOW displays ranges of moisture contents for the 10-hour fuel size class that results in a specific weighted fuel moisture, for a given 1-hour fuel moisture. MOISTURE also produce a table that shows for a given herbaceous moisture content, the range of woody fuel moisture that results in a specific weighted live fuel moisture.

3. Availability. Contact agency fire management staff for information on obtaining access to FIRE 1, NEWMDL, and TSTMDL. A copy of the complete BEHAVE program (including FIRE 2 and RXWINDOW) that runs on an IBM compatible computer can be purchased through a government contract at a low cost. The program disks will become available through the Publications Management System at the National Interagency Fire Center.

D. Fire Effects

1. Models within BEHAVE. There are few fire effects that relate directly to fire behavior, the activity of the flaming front of the fire. However, two programs within the BEHAVE system predict two effects, crown scorch height, and tree mortality, that can be directly or indirectly related to fire behavior. Access to both of these programs is through the BEHAVE system, described in section C. of this chapter.

a. SCORCH. A module of the FIRE 1 program of BEHAVE, SCORCH predicts lethal crown scorch heights from flame length, ambient air temperature, and midflame windspeed. This model estimates the maximum height in the convection column at which the lethal temperature for live crown foliage is reached, assumed to be 140 F (60 C). Scorch heights can be estimated during a prescribed fire operation, based on observations of the flame length, and ignition can be adjusted accordingly if desired scorch heights are not being achieved. SCORCH can be run by linking it to outputs from DIRECT. A more detailed description of this model can be found in Andrews and Chase (1989).

The SCORCH model has several limitations. It was developed for flat ground, so should be used on slopes with care. The model may not be valid outside the range of conditions for which it was developed, with fireline intensities ranging from 19 to 363 Btu per foot per second, equivalent to flame lengths of 1.8 to 6.8 feet (0.5 to 2.1 meters). Air temperatures are 73 to 88 F (23 to 31 C), and midflame windspeeds are 1.5 to 3 miles per hour (3.4 to 4.8 kilometers per hour). Under these conditions, scorch heights ranged from 6.5 to 56 feet (2 to 17 meters). Also, this model considers the heat released by the flaming front of the fire, not from the long-term burnout of large fuels. If significant amounts of residual burnout of large diameter fuels is anticipated, expected or observed flame length resulting from this burnout can be entered directly, instead of using the flame length calculated by BEHAVE in DIRECT.

b. MORTALITY. Tree mortality is predicted by the MORTALITY module of BEHAVE, also located in the FIRE 1 program. The model was developed by Reinhardt and Ryan (1988b), and its use within the BEHAVE program is described in Andrews and Chase (1989). MORTALITY predicts the percentage of tree mortality from estimates of crown and bole damage for a specific species, as different species have varying abilities to survive a set amount of damage. Data on mortality was collected from the following species, which can be specified when running the model: western larch, Douglas-fir, western hemlock, Engelmann spruce, western red cedar, lodgepole pine, and subalpine fir.

One can select one of these species to represent a species not listed if the bark thickness is similar. Inputs required to run this program are scorch height, tree height, crown ratio, and bark thickness, which is calculated from the species of tree and its diameter at breast height. Percentage of crown volume scorched is calculated from scorch height, tree height, and crown ratio. Bole damage is assumed to be proportional to bark thickness. The output is given in percent mortality. A 30 percent mortality means that 30 of 100 trees would be expected to die if subjected to the same fire, or that there is a 30 percent probability that any individual tree would die.

A linked run can be made from DIRECT to SCORCH to MORTALITY. Flame length can be calculated for a range of windspeeds in DIRECT. From these values, SCORCH will calculate a range of scorch height values, which provide one of the inputs to MORTALITY.

The model is limited by the assumption that the fire is of an average duration. Mortality may be under predicted if a fire of long duration occurs, caused by consumption of extremely dry duff or large diameter fuel. If fuel is very light or patchy, mortality may be over estimated.

2. First Order Fire Effects Model (FOFEM). The FOFEM program computes duff and woody fuel consumption, mineral soil exposure, fire-caused tree mortality, and smoke production for forest stands (Keane et al. 1990). A current version of the program is being tested by field users. Future versions will allow prediction of soil heating and successional changes. Default input values are derived from fuel models provided for natural and activity fuels by many forest cover types. For further information, contact the Fire Effects Research Work Unit at the Intermountain Fire Sciences Laboratory, Missoula, Montana.

3. CONSUME. CONSUME is a PC based software program that predicts the amount of fuel consumption on logged units based on weather data, the amount and moisture content of fuels, and other factors that describe a burn unit (Ottmar et al. 1993). The program allows a resource manager to determine when and where to conduct a prescribed fire to achieve desired objectives, while reducing impacts on other resources. CONSUME can be used for most broadcast and understory burns on forest lands where the dead woody fuels are relatively homogeneous. The program applies to western forests dominated by Douglas-fir, western hemlock, red alder, lodgepole pine, or mixed conifer species. Program disks and the users guide are available through the Publications Management System at NIFC.

4. Fire Effects Information System. The Fire Effects Information System (FEIS) is a computerized information storage and retrieval system that contains detailed information about the effects of fire on specific plants, plant communities, and wildlife species. Plant species information, for example, is organized into sub-categories of distribution and occurrence; value and use; botanical and ecological characteristics; fire ecology; and fire effects. Descriptions of the results of fire effects case studies are included if available. The FEIS is not a typical bibliographic data base that lists citations with key words and abstracts. The Fire Effects System provides information in a text format, providing reviews of the key facts in the literature, summarized into appropriate sub-categories. Numerical codes in the text refer to citations listed in a references section included in each species write-up. Where conflicting information about plant response has been found, interpretations are made if differences in season, burning conditions, or ecotype, for example, can explain why observed variations occurred. Information about wildlife species and ecosystems is handled in a similar fashion.

The system was developed by the U.S. Forest Service Intermountain Fire Sciences Laboratory in Missoula, Montana, and money for development of the prototype data base was provided by the BLM. Many plant species of ecosystems managed by the Bureau are presently in the system. Interagency funding is being used to expand the database to include species of the eastern U.S. and Alaska, as well as additional species of the western U.S.

The Citation Retrieval System (CRS) is an associated program that contains all of the references used in compiling species and plant community information for the FEIS. The CRS can be searched for a specific citation, author, or key word. It can prepare a bibliography from a list of citation index numbers selected by the user from a species write-up.

The FEIS and CRS are available on the Forest Service Intermountain Region computer in Ogden, Utah. Access is through the Forest Service Data General System, or by phone modem from any personal computer with software that allows communication with a Data General computer. There is no cost for PC users other than telephone line charges. Data can be saved to a temporary file on the main frame computer, and sent over phone lines to the user's computer. Department of Interior employees can contact their national fire management offices to obtain access information. U.S. Forest Service employees can obtain assistance from their regional FEIS coordinator. States provide information through their State FEIS coordinator.

E. Smoke Modeling.

1. SASEM. The Simple Approach Smoke Estimation Model (SASEM) is a tool for the analysis of smoke dispersion from prescribed fires (Sestak and Riebau 1988). It is a screening model, in that it uses simplified assumptions and tends to over predict impacts, yielding conservative results. If violations of air quality standards are not predicted by SASEM, it is unlikely that they will occur. Inputs to the model include basic descriptions of the fuels, such as type and loading, expected fireline intensity, and expected burn duration. Windspeed and direction, dispersion conditions, and average mixing height are considered, as well as distance and direction of the fire from sensitive receptors. The model calculates fuel consumption and particulate emission factors from fuel loading and expected fireline intensity. Model outputs include maximum particulate concentration and the distance from the fire at which it will occur, ranges of distances from the fire at which any primary or secondary particulate standards would be violated, and the reduction in visual range at selected receptors. Outputs are given in tabular fashion for a range of dispersion and windspeed conditions.

SASEM is extremely simple to use, and requires no data inputs that are not normally acquired as part of the prescribed fire planning process. The program is available on floppy disks for operation on IBM compatible machines. For further information, contact agency air resource or fire management specialists, or the air quality staff at the Environmental Science and Technology Center, National Biological Survey, Fort Collins, Colorado.

2. TSARS. The following discussion is taken from Sestak (et al. 1991). The Tiered Smoke/Air Resources System, TSARS, allows fire management field officers to test fire prescriptions for smoke management problems. Models with a high degree of rigor can be used to solve more complex problems, however, higher user proficiency is required.

a. Existing components. Models currently in the system include SASEM, explained in item E.1. above, EPM, and VALBOX.

(1) The Emission Production Model, EPM, is a more elaborate model of heat and particulate production than SASEM. Originally designed for forest fuels, particularly logging slash, data are presently being collected to broaden the model to other fuel types, particularly rangeland fuels.

(2) VALBOX models an airshed in complex terrain. Air in a mountain valley is divided into a series of connecting boxes, with dimensions calculated from topographic map data. This model best describes conditions when an inversion exists and air is stagnant.

b. Proposed components. BEHAVE, described in Section C. of this chapter, when added to the TSARS system, will expedite the running of EPM and SASEM because many of their input values are contained in the standard fire behavior fuel models used in BEHAVE. Use of these models together will allow consideration of smoke impacts when developing prescribed fire prescriptions.

TAPAS, the Topographic Air Pollution Analysis System, is a set of meteorological and pollution dispersion models suitable for use with multiple emission sources in complex terrain. Two models contained in TAPAS, WINDS and CITPUFF, will be specialized in the TSARS program for use in prescribed fire planning. WINDS is a two dimensional wind field model. A three dimensional wind model in TAPAS can be used by if elevation grid databases are created, information that is generally available in in Geographic Information Systems.

Wind fields created by the two or three dimensional models can be used with a final proposed component of TSARS. CITPUFF approximates the dispersion of a pollutant as it follows a path across a simulation area. The emission information required by this model would be provided by SASEM or EPM emission calculations.

It is intended that TSARS be available on the second generation IAMS system, and also on IBM compatible personal computers. For more information, contact air quality staff, Environmental Science and Technology Center, National Biological Survey, Fort Collins, Colorado.

F. Library Services

The literature search services maintained by Federal Libraries are valuable sources of computerized information helpful for managing fire effects. The Bureau of Land Management Library at the Denver Federal Center, for example, has the capability of making on-line searches of several hundred data bases that include periodicals, books, reports, and other publications. Some data bases provide abstracts along with full citations. The user works with a Library staff person by defining the kind of information desired, as well as specifying key words to be used in the search. Bibliographies can be requested by subject area, author, report number, or other category. The library can also provide copies of articles, and loan books in their collection and through inter-library loan. Any BLM employee can contact the Library at the BLM Service Center in Denver for assistance. The phone number is 303/236-6646.

The Alaska Resources Library provides a full range of library services to all Federal employees, particularly in the natural resources field. The Library is located in the Federal Building in Anchorage, where it is administered by the BLM. The phone number is 907/271-5025; FAX is 907/271-5965.

The Department of the Interior Natural Resources Library provides a full range of library services to USDI employees in response to telephone and written requests. They are located in the Main Interior Building, Washington, D.C.; their phone number is 202/208-5815.

National Park Service employees can contact the NPS Service Center at Harper's Ferry, Virginia or Denver for library assistance. The phone number at Harper's Ferry is 304/535-6371; Denver is 303/969-2100.

U. S. Forest Service employees can obtain a full range of library services through FS INFO, available to them on the Data General System through the Information Center process. Both Forest Service Research and National Forest System Employees can seek assistance from the FS INFO center located in at the Forest and Range Experiment Station in their geographic region.

G. Summary

Computer technology and applications are developing so quickly that any list of software is incomplete as soon as it is published. Specialized computer programs, called expert systems, may be available in the next few years. Expert systems are being developed or planned that can assist in the development of fire prescriptions to meet specific resource objectives, and to achieve specific fire effects. Agency fire management and air quality specialists can be contacted for information about future computer software development.

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Fire Effects Guide

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GLOSSARY OF TERMS

- A -

absolute value: the absolute value represents the distance that a positive or negative number is from zero, when numbers are arrayed on a line with negative numbers to the left of zero and positive numbers to the right of zero. The absolute value of a positive number is the number itself, whereas the absolute value of a negative number is the opposite (positive) number (Batchelet 1976).

accelerated erosion: erosion much more rapid than normal, natural, or geologic erosion, primarily as a result of the influence of the activities of humans, or, in some cases, of other animals or natural catastrophes that expose bare surfaces, for example, fires.

accuracy: the closeness of a measured or computed value to its true value. Accuracy cannot be determined from a sample, and usually remains unknown. (See precision.)

active crown fire: a fire in which a solid flame develops in the crowns of trees, but the surface and crown phases advance as a linked unit dependent on each other.

active layer: soil layer that overlies permafrost that thaws every summer (Viereck and Schandelmeier 1980).

activity fuels: fuels resulting from, or altered by, forestry practices such as timber harvest or thinning, as opposed to naturally created fuels. (See natural fuels.)

aeolian (eolian): movement of material, such as soil, through wind action.

aerial fuels: the layer of fuels that is above the surface fuels, including living tree and shrub crowns, mosses, lichens, vines, and dead branch material.

age class: classes that define the ages of individuals in discrete units, such as 0 to 5 years, or 6 to 20 years.

algal bloom: proliferation of living algae on the surface of lakes, streams, or ponds that is stimulated by nutrient, especially nitrogen or phosphate, enrichment.

alkaline soil: any soil with a pH value greater than 7.0. Often used interchangeably with "basic soil."

allelopathy: inhibition by a plant of the germination, establishment, and growth of seedlings.

ammonification: the biochemical process whereby ammoniacal nitrogen is released from nitrogen containing organic compounds.

analysis of covariance (ACOVA): test that combines regression with analysis of variance. In general, variation in *y* that is associated with *x* is removed from the error variance, which results in more precise estimates from more powerful tests. An example in fire management is the case where plants of different sizes are measured before burning; because plant size may affect postburn response, the effect of plant size is "controlled" so that differences due to burning will be apparent.

analysis of variance (ANOVA or **AOV):** test used when statistical inferences are to be made about more than two means. Test can "control" one or more sources of variation, depending on model and experimental design.

anion: negatively charged ion.

annual plant: a plant completing its life cycle in a year or less (Benson 1967).

Aridisol: soil with pedogenic horizons, low in organic matter, that are never moist as long as three consecutive months. They also have one or more of the following diagnostic horizons, including argillic, natric, cambic, calcic, petrocalcic, gypsic, or salic, and may have a duripan. Aridisols are approximately equal to Desert, Reddish Desert, Sierozem, Solonchak, some Brown and Reddish Brown, and associated Solonetz soils of the pre-1966 classification scheme.

arithmetic mean: the mean (or average) of sample data; it provides an unbiased estimate of the parametric mean; designated by x. (NOTE: There are other kinds of means, such as harmonic, geometric, and parametric.)

arrangement: see fuel arrangement.

ASCII: American Standard Code for Information Interchange. A code for transmitting information asynchronously on local and long distance communication lines; representing a standard set of letters, numbers, and control characters.

attributes: those variables that cannot be measured, but must be expressed qualitatively. (See variable.)

available fuel: the portion of the total fuel on the site that would actually burn under a given set of environmental conditions.

avoidance: a smoke emission control strategy that considers meteorological conditions when scheduling prescribed fires in order to avoid incursions into smoke sensitive areas (Mathews et al. 1985).

axil: the upper side of the point where a leaf meets a stem, or a branch meets another branch or the main stem of a plant.

axillary bud: a bud in a leaf axil.

- B -

backing fire: a fire, or that part of a fire, spreading or set to spread into the wind, or down a slope.

basal cover: the vertical projection of the root crown onto the ground. (See cover and foliar cover.)

BEHAVE: a system of two interactive computer programs for modelling fuel and fire behavior.

bias: systematic distortion that may be due to measurement error, method of selecting the sample,

etc. An example is the use of an uncalibrated balance that consistently overestimates mass by 10 grams, or neglecting to subtract tare weight (weight of the container) from packaged samples.

biennial plant: a plant that completes its life cycle in two years. Biennial plants usually produce only

basal leaves above ground the first year and both basal leaves and flowering stems the second (Benson 1967).

broadcast burning: allowing a prescribed fire to burn over a designated area within well-defined boundaries for reduction of fuel hazard, as a resource management treatment, or both.

Btu: British thermal unit. The amount of heat needed to raise the temperature of one pound of water (one pint) one degree Fahrenheit.

bud: a vegetative growing structure at the tip of a stem or branch with the enclosing scale leaves or

immature leaves; a young flower bud that has not yet opened. A vegetative bud may also be located along the surface of roots or rhizomes, or buried in woody stem or root tissue (Benson 1967).

bud primordia: a cluster of plant cells with the physiological potential to develop into a bud or actively growing shoot.

bulb: an underground bud covered by fleshy scales, the coating formed from the bases of leaves (Benson 1967).

bulk density: weight per unit volume. For fuels, this is usually expressed as pounds per cubic foot; for soils, grams per cubic centimeter.

burl: a mass of woody tissue from which roots and stems originate, and which is often covered with dormant buds (James 1984).

burn severity: a qualitative assessment of the heat pulse directed toward the ground during a fire. Burn severity relates to soil heating, large fuel and duff consumption, consumption of the litter and organic layer beneath trees and isolated shrubs, and mortality of buried plant parts.

- C -

cambium: a layer of dividing plant cells which add during each growing season a layer of woody material (largely xylem) on their inner side toward the center of the stem or root and a layer of bark (phloem and associated tissues) on the outer side (Benson 1967).

carbohydrates: starches and sugars manufactured by a plant and used to provide energy for metabolism, and structural compounds for growth (Trlica 1977).

carrier fuels: the fuels that support the flaming front of the moving fire.

cation: positively charged ion. Common soil cations include calcium, magnesium, sodium, potassium, and hydrogen.

caudex: a largely underground stem base which persists from year to year and each season produces leaves and flowering stems (Benson 1967).

chain: unit of measure in land survey, equal to 66 feet (20 meters) (80 chains equal one mile). Commonly used to report fire perimeters and other fireline distances, chains can be easily converted to acreage (e.g., 10 square chains equal one acre).

Class 1 Area: geographic areas designated by the Clean Air Act where only a very small amount or increment of air quality deterioration is permissible. Class 1 Areas include specified National Parks, Wilderness Areas, and certain Indian reservations.

clastic: being able to readily break into small fragments or pieces.

climax: the highest ecological development of a plant community capable of perpetuation under the prevailing climatic and edaphic conditions (Range Term Glossary Committee 1974).

clone: a group of individuals propagated vegetatively from a single individual of seedling origin (Barnes 1966 in Jones 1985). Individuals in a clone are genetically the same plant.

colonizer: species that establish on a burned (or otherwise denuded) site from seed (Stickney 1986).

combustion: consumption of fuels by oxidation, evolving heat, flame, and/or incandescence.

combustion efficiency: the relative amount of time a fire burns in the flaming phase of combustion, as compared to smoldering combustion. A ratio of the amount of fuel that is consumed in flaming combustion compared to the amount of fuel consumed during the smoldering phase, in which more of the fuel material is emitted as smoke particles because it is not turned into carbon dioxide and water.

confidence level: the percentage confidence that a statement is true. If data are normally distributed about an average value, the statement 'within 10 percent of the mean at the 80 percent confidence level' would indicate that a sample is likely to be within 10 percent of the true average value of the population 80 percent of the time.

continuity: see fuel continuity.

continuous variables: those variables which, at least theoretically, can assume an infinite number of values between any two fixed points. An example is fuel load, which theoretically can be anywhere between zero and infinity. (See discrete variables.)

control strategy: a way of implementing a prescribed fire that manages smoke output. (See avoidance, dilution, and emission reduction.)

convection column: the thermally induced ascending column of gases, smoke, water vapor, and particulate matter produced by a fire.

cookbook approach: to follow a particular procedure without deviation.

coordinated resource management: a process that directly involves everyone concerned with resource management in a given planning area.

corm: a bulb-like structure formed by enlargement of the stem base, sometimes coated with one or more membranous layers (Benson 1967).

cover: the area on the ground covered by the combined aerial parts of plants expressed as a percent of the total area. (See basal cover and foliar cover.)

criteria pollutants: those air pollutants designated by the Environmental Protection Agency as poten- tially harmful and for which ambient air standards have been set to protect the public health and welfare. The criteria pollutants are carbon monoxide, particulate matter, sulfur dioxide, nitrogen dioxide, lead, and ozone.

crown consumption: combustion of the twigs, and needles or leaves of a tree during a fire.

crown fire: a fire that advances by moving among crowns of trees or shrubs.

crown ratio: the ratio of live crown to tree height.

crown scorch: causing the death of tree foliage by heating it to lethal temperature during a fire, although the foliage is not consumed by the fire. Crown scorch may not be apparent for several weeks after the fire.

crown scorch height: the height above the surface of the ground to which a tree canopy is scorched.

crowning potential: a probability that a crown fire may start, calculated from inputs of foliage moisture content and height of the lowest part of the tree crowns above the surface.

- D -

data: the facts collected during observations; used as a plural noun, i.e., "data are," or "data were." (See datum.)

datum: a single fact collected during observation; the singular of "data." (See data.)

dead fuels: naturally occurring fuels without living tissue, in which the moisture content is governed almost entirely by absorption or evaporation of atmospheric moisture (relative humidity and precipitation).

decreaser species: plant species of the original vegetation that decrease in relative amount under overuse by grazing or browsing animals. Commonly termed decreasers.

degrees of freedom: the quantity n or n-1, where n is the number of observations (population or sample size) upon which a variance has been based; degrees of freedom is usually designated by the abbreviation "*df*."

density: the number of plants or parts of plants per unit area.

designated area: those areas identified as principal population centers or other areas requiring protection under state or federal air quality laws or regulations.

desired plant community: a plant community which produces the kind, proportion, and amount of vegetation necessary for meeting or exceeding the land use plan goals and activity plan objectives established for the site.

diffusion: the net movement of gas molecules from areas with higher concentration of that gas to areas with lower concentration.

dilution: a control strategy used in managing smoke from prescribed fires in which smoke concentration is reduced by diluting it through a greater volume of air, either by scheduling during good dispersion conditions or burning at a slower rate (Mathews et al. 1985).

disclimax: (disturbance climax) a stable plant community which is not the climatic or edaphic climax and which is perpetuated by man or his domestic animals (Odum 1966).

discrete variables: those variables that have only certain fixed numerical values, with no intermediate values possible in between; also known as discontinuous or meristic variables. An example is the number of offspring per litter, where only integers (whole numbers) are possible. (See continuous variables.)

diversity: the relative degree of abundance of wildlife species, plant species, communities, habitats, or habitat features per unit of area (Thomas 1979).

duff: the partially decomposed organic material of the forest floor that lies beneath the freshly fallen twigs, needles and leaves. The fermentation and humus layers of the forest floor (Deeming et al. 1977).

- E -

ecological condition (range): the existing state of the vegetation on a site compared to the natural potential (climax) plant community for that site. This term is used interchangeably with "range condition" and describes the deviation from the climax condition according to four arbitrary condition classes. Not synonymous with "forage condition" which does not relate to site potential.

ecological niche: the role or function a particular organism plays in the environment (Hanson 1962).

ecological site: a distinctive geographic unit that differs from other kinds of geographic units in its ability to produce a characteristic natural plant community. An ecological site is the product of all the environmental factors responsible for its development. It is capable of supporting a native plant community typified by an association of species that differs from that of other ecologic sites in the kind or portion of species or in total production.

ecology: the study of the interrelationships of organisms with one another and with the environment (Hanson 1962).

ecosystem: an interacting natural system including all the component organisms together with the abiotic environment (Hanson 1962).

ecotone: the area influenced by the transition between plant communities or between successional stages or vegetative conditions within a plant community (Thomas 1979).

edge: the place where plant communities meet or where successional stages or vegetative conditions within plant communities come together (Thomas 1979).

edge effect: the increased richness of flora and fauna resulting from the mixing of two communities where they join (Thomas 1979).

effective windspeed: a value that combines the speed of the wind with the additive effect of slope when a fire is burning up or across a slope.

emission: a release into the outdoor atmosphere of air contaminants such as smoke.

emission factor: the mass (weight) of particulate matter produced per unit mass of fuel consumed (expressed as grams per kilogram or pounds per ton).

emission inventory: a listing by source of the amounts of air pollutants discharged into the atmosphere.

emission reduction: a strategy for controlling smoke from prescribed fires that minimizes the amount of smoke output per unit area treated.

equilibrium moisture content: the moisture content that a fuel particle will attain if exposed for an indefinite period in an environment of specified constant temperature and humidity. When a fuel particle has reached its EMC, the net exchange of moisture between it and its environment is zero (Deeming et al. 1977).

eurytopic: having a wide range of suitable ecological conditions (Pennak 1964).

eutrophication: the process whereby water becomes excessively rich in nutrients and correspondingly deficient, at least seasonally, in oxygen. Often accompanied or followed by algal blooms.

exfoliation: the separation of concentric layers of rock from the original rock mass.

experimental design: the process of planning an experiment or evaluation so that appropriate data will be collected, which may be analyzed by statistical methods resulting in valid and objective conclusions. Examples include Completely Random Design, Randomized Block Design, Latin Square, Factorial Experiment, Split-Plot Design, and Nested Design.

experimental error: a measure of the variation which exists among observations on experimental units that are treated alike; "natural" variation.

- F -

feeder roots: small diameter roots that collect most water and nutrients for a plant, usually located near the soil surface.

fine fuels: small diameter fuels such as grass, leaves, draped pine needles, and twigs, which when dry, ignite readily and are rapidly consumed.

fire behavior: the manner in which a fire burns in response to the variables of fuel, weather, and topography.

fire intensity: see fireline intensity.

Fire Behavior Prediction System: a system that uses a set of mathematical equations to predict certain aspects of fire behavior in wildland fuels when provided with data on fuel and environmental conditions (Rothermel 1983).

fire regime: periodicity and pattern of naturally occurring fires in a particular area or vegetative type, described in terms of frequency, biological severity, and areal extent (Tande 1980).

fire severity: see burn severity.

fire spread model: a set of physics and empirical equations that form a mathematical representation of the behavior of fire in uniform wildland fuels (Rothermel 1972).

fire treatment: the use of prescribed fire to accomplish a specified objectives.

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 the entire fire area or only a hot spot within the area.

fireline intensity: the heat released per unit of time for each unit length of the leading fire edge. The primary unit is Btu per lineal foot of fire front per second (Byram 1959 in Albini 1976).

firing pattern: see ignition pattern.

firing technique: see ignition pattern.

first order fire effects (FOFE): the direct and immediate effects of fire.

flame length: the average length of flames when the fire has reached its full, forward rate of spread, measured along the slant of the flame from the midpoint of its base to its tip.

flaming phase: the phase of combustion in which gases distilled from fuels rapidly combine with atmospheric oxygen, producing visible flames.

FLPMA: the Federal Land Policy and Management Act of 1976 (Public Law 94-579, 90 Stat. 2743, 43 USC 1701).

foliar cover: the projection of all plant parts vertically onto the ground. (See cover, and basal cover.)

forb: a plant with a soft, rather than permanent woody stem, that is not a grass or grasslike plant.

forward rate of spread: the speed with which a fire moves in a horizontal direction across the landscape, usually expressed in chains per hour or feet per minute.

frequency of occurrence: a quantitative expression of the presence or absence of individuals of a species in a population; the ratio between the number of sample units that contain a species and the total number of sample units.

fuel: combustible plant material, both living and dead that is capable of burning in a wildland situation.

fuel arrangement: the spatial distribution and orientation of fuel particles within a fuel bed.

fuel bed: an array of fuels usually constructed with specific loading, depth, and particle size, to meet experimental requirements; also commonly used to describe the fuel composition in natural settings.

fuel bed depth: average height of surface fuels contained in the combustion zone of a spreading fire front.

fuel continuity: the degree or extent of continuous or uninterrupted distribution of fuel particles in a fuel bed, a critical influence on a fire's ability to sustain combustion and spread. This applies both to aerial fuels and surface fuels.

fuel depth: see fuel bed depth.

fuel loading: the weight of fuels in a given area, usually expressed in tons per acre, pounds per acre, or kilograms per square meter.

fuel model: a characterization of fuel properties of a typical field situation. A fuel model contains a complete set of inputs for the fire spread model.

fuel moisture content: the amount of water in a particle of fuel, usually expressed as a percentage of the oven dry weight of the fuel particle.

fuel size class: a category used to describe the diameter of down dead woody fuels. Fuels within the same size class are assumed to have similar wetting and drying properties, and to preheat and ignite at similar rates during the combustion process.

- G -

glowing phase: phase of combustion in which a solid surface of fuel is in direct contact with oxygen, and oxidation occurs, usually accompanied by incandescence, and little smoke production.

graminoid: grasslike plant, including grasses, sedges, rushes, reeds, and cattails.

gravimetric: of, or pertaining to, measurement by weight.

grazing management (strategy): the manipulation of the grazing use on an area in a particular pattern, to achieve specific objectives.

grazing pattern: dispersion of livestock grazing within a management unit or area.

ground fire: fire that burns the organic material in the soil layer (e.g. a "peat fire") and often also the surface litter and low-growing vegetation.

ground fuels: all combustible materials below the surface litter layer, including duff, tree and shrub roots, punky wood, dead lower moss and lichen layers, and sawdust, that normally support glowing combustion without flame.

growth stage: the relative ages of individuals of a species, usually expressed in categories such as seedlings, juvenile, mature, and decadent.

guild: see habitat guild.

- H -

habitat: the sum total of environmental conditions of a specific place occupied by a wildlife species or a population of such species (Thomas 1979).

habitat guild: a group of species having similar ecological requirements and/or foraging strategies and therefore having similar roles in the community (Cooperrider et al. 1986).

heading fire: a fire front spreading, or ignited to spread with the wind, up a slope, or influenced by a combination of wind and slope.

heat content: the net amount of heat that would be given off if fuel burns when it is absolutely dry, noted as Btu per pound of fuel.

heat per unit area: total amount of heat released per unit area as the flaming front of the fire passes, expressed as Btu/square foot; a measure of the total amount of heat released in flames.

heavy fuels: dead fuels of large diameter (3.0 inches or larger) such as logs and large branchwood.

height: the vertical measurement of vegetation from the top of the crown to ground level.

herbivorous: feeding on plants; phytophagous (Cooperrider et al. 1986).

humidity: see relative humidity.

hydrophobicity: resistance to wetting exhibited by some soils, also called water repellency. The phenomena may occur naturally or may be fire-induced. It may be determined by water drop penetration time, equilibrium liquid-contact angles, solid-air surface tension indices, or the characterization of dynamic wetting angles during infiltration.

- I -

ignition method: the means by which a prescribed fire is ignited, such as hand-held drip torch, heli- torch, and backpack propane tanks.

ignition pattern: the configuration and sequence in which a prescribed fire is ignited. Patterns include, for example, spot fire, strip-head fire, and ring fire (same as ignition technique).

ignition technique: see ignition pattern.

illuviation: soil development process by which materials are translocated from an upper soil horizon and immobilized in a soil horizon at a lower level in the soil profile.

imbibe: to absorb liquid or moisture.

Inceptisol: soil that is usually moist and has pedogenic horizons of alteration of parent material but not of illuviation. Generally, the direction of development is not evident, or is too weak to classify in another soil order. Inceptisols are approximately equal to Ando, Sol Brun Acide, some Brown Forest, Low-Humic Gley, and Humic Gley soils of the pre-1966 classification scheme.

increaser species: plant species of the original vegetation that increase in relative amount, at least for a time, under overuse. Commonly termed increasers.

independent crown fire: a fire that advances in the tree crowns alone, not requiring any energy from the surface fire to sustain combustion or movement.

intensity: see fireline intensity.

interspersion: the intermixing of plant species and plant communities that provide for animals in a defined area (Thomas 1979).

introduced plant species: a species not a part of the original fauna or flora of an area.

invader species: plant species that were absent in undisturbed portions of the original vegetation and will invade under disturbance or continued overuse. Commonly termed invaders.

- J -

juxtaposition: the arrangement of stands of vegetation in space (Thomas 1979).

- K -

Kcal: a kilogram-calorie is the amount of heat needed to raise the temperature of one kilogram of water (1 liter) by 1 degree Celsius.

key forage species: forage species of particular importance in the plant community or which are important because of their value as indicators of change in the community.

- L -

ladder fuels: fuels that can carry a fire from the surface fuel layer into the aerial fuel layer, such as a standing dead tree with branches that extend along its entire length.

leach: removal of soluble constituents from ashes or soil by percolation of water.

life-form: a group of wildlife species whose requirements for habitat are satisfied by similar successional stages within given plant communities (Thomas 1979).

lignotuber: a mass of woody tissue from which roots and stems originate, which often covered with dormant buds (James 1984); same as root crown.

litter: the top layer of forest floor, typically composed of loose debris such as branches, twigs, and recently fallen leaves or needles; little altered in structure by decomposition. The L layer of the forest floor (Deeming et al. 1977). *Also* loose accumulations of debris fallen from shrubs, or dead parts of grass plants laying on the surface of the ground.

live fuel moisture content: ratio of the amount of water to the amount of dry plant material in living plants.

live fuels: living plants, such as trees, grasses, and shrubs, in which the seasonal moisture content cycle is controlled largely by internal physiological mechanisms, rather than by external weather influences.

live herbaceous moisture content: ratio of the amount of water to the amount of dry plant material in herbaceous plants, i.e., grasses and forbs.

live woody moisture content: ratio of the amount of water to the amount of dry plant material in shrubs.

- M -

mast: the fruit of trees suitable as food for livestock and wildlife (Ford-Robertson 1971).

mean: see arithmetic mean.

meristem: growing points of grasses, from which leaf blade elongation occurs during active growing periods.

mesotopic: having an intermediate range of suitable ecological conditions.

mho: meter/kilogram/second unit of electrical conductance, equal to the conductance of a conductor in which a potential difference of one volt maintains a current of one ampere.

midflame windspeed: the speed of the wind measured at the midpoint of the flames, considered to be most representative of the speed of the wind that is affecting fire behavior.

millimho: a unit of electrical conductance, equal to 0.001 mho.

moisture content: see fuel moisture content.

moisture of extinction: the moisture content of a specific fuel type above which a fire will not propagate itself, and a firebrand will not ignite a spreading fire.

Mollisol: soil with nearly black, organic-rich surface horizons and high supplies of bases; they may accumulate large amounts of organic matter in the presence of calcium. They have mollic epipedons and base saturation greater than 50% in any cambic or argillic horizon and are approximately equal to Chestnut, Chernozem, Brunizem, Rendzina, some Brown, Brown Forest, and associated Solonetz and Groundwater Podzols of the pre-1966 classification scheme.

mosaic: the intermingling of plant communities and their successional stages in such a manner as to give the impression of an interwoven design (Ford-Robertson 1971).

muck: a highly decomposed layer of organic material in an organic soil (Buckman and Brady 1966).

mycorrhiza (pl. mycorrhizae): a mutually beneficial (symbiotic) association between a plant root and a fungus, that enhances the ability of the root to absorb water and nutrients.

- N -

National Fire Danger Rating System: a multiple index scheme designed to provide fire and land management personnel with a systematic means of assessing various aspects of fire danger on a day-to-day basis.

native species: a species which is a part of the original fauna or flora of the area in question.

natural fuels: fuels resulting from natural processes and not directly generated or altered by land management practices. (See activity fuels.)

NFDRS: see National Fire Danger Rating System.

niche: (habitat niche) the peculiar arrangement of food, cover, and water that meets the requirements of a particular species.

NIFMID: National Interagency Fire Management Integrated Database.

nonparametric tests: statistical testing techniques that are not dependent on a given distribution. (See parametric tests.)

normal distribution: a continuous frequency distribution whose graphic representation is a bell-shaped curve that is symmetrical about the mean, which by definition has a mean of 0 and a variance of 1. Many other types of distributions exist that have different shaped curves, such as hypergeometric, Poisson, and binomial.

number: the total population of a species or classification category in a delineated unit, a measure of its abundance.

nutrient: elements or compounds that are essential as raw materials for organism growth and develop ment, such as carbon, oxygen, nitrogen, and phosphorus. There are at least 17 essential nutrients.

- O -

obligate: restricted to a particular condition of life, as an obligate seeder, a plant that can only reproduce by seed.

off-site colonizers: plants that germinate and establish after a disturbance from seed that was carried from off of the site (Stickney 1986).

onsite colonizers: plants that germinate and establish after a disturbance from seed that was present on the site at the time of the disturbance (Stickney 1986).

one-hour timelag fuels: dead fuels consisting of dead herbaceous plant material and roundwood less than 0.25 inches (0.64 cm) in diameter, expected to reach 63 percent of equilibrium moisture content in one hour or less.

one-hundred hour timelag fuels: dead fuels consisting of roundwood in the size range from 1.0 to 3.0 inches (2.5 to 7.6 cm) in diameter, estimated to reach 63 percent of equilibrium moisture content in one hundred hours.

one-thousand hour timelag fuels: dead fuels consisting of roundwood 3.0 to 8.0 inches (7.6 to 20.3 cm) in diameter, estimated to reach 63 percent of equilibrium moisture content in one thousand hours.

organic matter: that fraction of the soil that includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population.

organic soil: a soil with a percentage content of organic matter greater than about 20 to 25 percent (Buckman and Brady 1966).

- P -

packing ratio: the percentage of a fuel bed that is composed of fuel particles, the remainder being air space among the individual particles (Burgan and Rothermel 1984); the fuel volume divided by fuel bed volume.

palatability: the relish that an animal shows for a particular species, plant or plant part; how agreeable the plant is to the taste.

parameter: a variable which can be measured quantitatively; sometimes, an arbitrary constant; associated with populations. One of the unknown values that determine a model. (See statistic.)

parametric tests: statistical tests that are based on normal distributions. (See nonparametric tests).

particle size: the size of a piece of fuel, often expressed in terms of size classes.

particulate matter: any liquid or solid particles present in the atmosphere. Particulate matter diameter is measured in microns.

passive crown fire: a fire in the crowns of trees in which trees or groups of trees torch, ignited by the passing front of the fire. The torching trees reinforce the spread rate, but these fires are not basically different from surface fires.

peat: a deposit of slightly or non-decayed organic matter (Buckman and Brady 1966).

percolation: passage of liquid through a porous body, as movement of water through soil.

perennial plant: a plant that continues to grown year after year (Benson 1967). (See annual plant and biennial plant.)

permafrost: a short term for "permanently frozen ground"; any part of the earth's crust, bedrock, or soil mantle that remains below 32 F (0 C) continuously for a number of years (Brown 1970 in Viereck and Schandelmeier 1980). (See active layer.)

petroglyph: a type of rock art in which a design is pecked into stone.

pH: the negative logarithm (base =10) of the hydronium ion concentration, in moles per liter. It is a numerical measure of acidity or alkalinity on a scale of 1 to 14, with the value of 7.0 being neutral.

phenology: the relationship of the seasonal sequence of climatic factors with the timing of growth and reproductive phases in vegetation, such as initiation of seasonal growth, time of blooming, time of seed set, and development of new terminal buds (Daubenmire 1968b).

phreatophyte: a plant that derives its water from subsurfaces, typically having roots that reach the water table, and is therefore somewhat independent of precipitation. Obligate phreatophytes require this situation, whereas facultative phreatophytes merely take advantage it.

pictograph: a type of rock art in which a design is painted onto stone.

pile burning: burning of logging slash that has been arranged into individual piles. (See broadcast burning.)

PM_{10}: particles with an aerodynamic diameter smaller than or equal to a nominal ten micrometers.

$PM_{2.5}$: particles with an aerodynamic diameter smaller than or equal to a nominal 2.5 micrometers.

population: all possible values of a variable; the entire group that is examined. (See sample.)

precision: the closeness of repeated measurements of the same quantity. (See accuracy.)

preignition phase: preliminary phase of combustion in which fuel elements ahead of the fire are heated, causing fuels to dry. Heat induces decomposition of some components of the wood, causing release of combustible organic gases and vapors.

prescribed burning: controlled application of fire to wildland fuels in either their natural or modified state, under specified environmental conditions that allows the fire to be confined to a predetermined area, and produce the fire behavior and fire characteristics required to attain planned fire treatment and resource management objectives.

prescribed fire: an intentionally or naturally ignited fire that burns under specified conditions that allow the fire to be confined to a predetermined area and produce the fire behavior and fire characteristics required to attain planned fire treatment and resource management objectives.

prescription: a written statement defining the objectives to be attained as well as the conditions of temperature, humidity, wind direction and speed, fuel moisture, and soil moisture, under which a fire will be allowed to burn. A prescription is generally expressed as acceptable ranges of the prescription elements, and the limit of the geographic area to be covered.

prevention of significant deterioration: a provision of the Clean Air Act with the basic intent to limit degradation of air quality, particularly in those areas of the country where the air quality is much better than standards specified in the Law.

probability: a measurement that denotes the likelihood that an event occurred simply by chance.

probability of ignition: the chance that a firebrand will cause an ignition when it lands on receptive fuels.

productivity: weight of dry matter produced in a given period by all the green plants growing in a given space (Daubenmire 1968b).

PSD: see prevention of significant deterioration.

pyrolysis: the thermal or chemical decomposition of fuel at an elevated temperature. This is the pre- ignition phase of combustion during which heat energy is absorbed by the fuel that, in turn, gives off flammable tars, pitches, and gases.

- R -

ramet: an individual member of a clone. For example, every individual stem in an aspen clone is a ramet.

random: the assignment of treatments to experimental units, or the selection of samples, such that all units or samples have an equal chance of receiving the treatment being estimated. It serves to assure unbiased estimates of treatment means and experimental error.

rate of spread: see forward rate of spread.

RAWS: see Remote Automated Weather Station.

reaction intensity: the rate of heat release, per unit area of the fire front, expressed as heat energy/area/time, such as Btu/square foot/minute, or Kcal/square meter/second.

regeneration: see vegetative regeneration.

regional haze: atmospheric haze over a large area with no attributable source.

relative frequency: see frequency of occurrence.

relative humidity: the ratio, in percent, of the amount of moisture in a volume of air to the total amount which that volume can hold at the given temperature and atmospheric pressure. Relative humidity is a function of the actual moisture content of the air, the temperature, and the atmospheric pressure (Schroeder and Buck 1970).

Remote Automatic Weather Station (RAWS): a self contained meteorological platform that automatically acquires, processes, and stores local weather data for subsequent transmission through a satellite to an earth receiving station.

reproduction: see vegetative reproduction.

residence time: the time required for the flaming zone of the moving front of a fire to pass a stationary point; the total length of time that the flaming front of the fire occupies one point.

residual colonizers: plants that germinate after a disturbance from seed that was present on the site (Stickney 1986).

respiration: oxidation of food in living cells, with the resulting release of energy; part of the energy is transferred to other compounds and some is used in the activation of certain cell processes (Meyer et al. 1973).

rhizome: a horizontal plant stem, growing beneath the surface, and usually covered with dormant buds.

root crown: a mass of woody tissue from which roots and stems originate, and which are often covered with dormant buds (James 1984); same as lignotuber.

running crown fire: a fire moving in the crowns of trees, dependent upon, or independent from the surface fire.

- S -

sample: part of a population; that portion of the population that is measured.

sample size: the number of items or observations in a sample; usually denoted by lower case letter n.

SASEM: Simple Approach Smoke Estimation Model (SASEM), a computer model for the analysis of smoke dispersion from prescribed fires. It is a screening model, in that it uses simplified assumptions and tends to over predict impacts, yielding conservative results.

second order fire effects (SOFE): the indirect effects of fire treatment that occur over the longer term.

seedbank: the supply of viable seeds present on a site. Seeds include those recently dispersed by plants, long-lived seeds buried in organic and soil layers, or those stored in cones in a tree canopy.

semi-serotinous: cones of coniferous trees that open and release their seeds over a period of years (Zasada 1986).

senescence: period of declining productivity after the period of most active growth, referred to both in terms of the seasonal life cycle of a plant, and the total life of a perennial plant.

seral: pertaining to a succession of plant communities in a given habitat leading to a particular climax association; a stage in a community succession (Cooperrider et al. 1986).

sere: the stages that follow one another in an ecological succession (Hanson 1962).

serotiny: storage of coniferous seeds in closed cones in the canopy of the tree. Serotinous cones of lodgepole pine do not open until subjected to temperatures of 45 to 50 C (113 to 122 F), causing the melting of the resin bond that seals the cone scales.

severity: see burn severity.

short-life species: a plant that grows several years before being replaced by a species more adapted to the changing site conditions.

simulation: a realistic visual portrayal which demonstrates the perceivable changes in landscape features caused by a proposed management activity. This is done through the use of photography, art work, computer graphics and other such techniques.

sinter: clustering of clay particles that occurs when pottery is fired.

SIP: see State Implementation Plan.

slash: concentrations of wildland fuels resulting from human activities such as logging, thinning, and road construction, and natural events such as wind. Slash is composed of branches, bark, tops, cull logs, uprooted stumps, and broken or uprooted trees.

smoldering phase: a phase of combustion that can occur after flames die down because the reaction rate of the fire is not high enough to maintain a persistent flame envelope. During the smoldering phase, gases condense because of the cooler temperatures, and much more smoke is produced than during flaming combustion.

soil structure: the combination or arrangement of primary soil particles, units, or peds. Examples include platy, prismatic, columnar, blocky, angular blocky, subangular granular, and crumb.

soil texture: the relative proportions of the various soil separates, primarily sand, clay, and silt. Subdivisions of the three basic separates, such as very fine sand, are often used.

spall: disintegration of a rock by breaking away of an outer layer.

species composition: a term relating the relative abundance of one plant species to another using a common measurement; the proportion (percentage) of various species in relation to the total on a given area.

species richness: a measurement or expression of the number of species of plants or animals present in an area; the more species present, the higher the degree of species richness (Thomas 1979).

spot fire: fire caused by flying sparks or embers outside the perimeter of the main fire.

spot forecast: a customized prediction of atmospheric conditions at a specific site that is issued by the National Weather Service, usually requested in connection with a wildfire incident or a prescribed fire.

spot weather forecast: see spot forecast.

spotting: production of burning embers in the moving fire front that are carried a short distance ahead of the fire, or in some cases are lofted by convective action or carried by fire whirls some distance ahead.

standard deviation: a measure of the variation, or spread, of individual measurements; a measurement which indicates how far away from the middle the statistics are; usually denoted by the lower case s for sample data; mathematically equal to the square root of variance.

State Implementation Plan: a plan that describes how a State intends to achieve Federal and State standards relative to the Clean Air Act, usually containing State regulations related to maintenance of air quality.

statistic: the number that results from manipulating raw data according to a specified procedure; associated with samples. (See parameter.)

statistics: the scientific study of numerical data based on natural phenomena.

stenotopic: having a narrow range of suitable ecological conditions (Pennak 1964).

stochastic: of, or pertaining to, randomness.

stolon: a branch of a plant which grows along the surface of the ground and produces plants and roots at intervals.

structure (vegetative): the form or appearance of a stand; the arrangement of the canopy; the volume of vegetation in tiers or layers (Thomas 1979).

succession: the process of vegetational development whereby an area becomes successively occupied by different plant communities of higher ecological order (Range Term Glossary Committee 1974).

successional change: see succession.

sum: the amount obtained by adding numbers or quantities; total; usually denoted by an upper case Greek sigma, .

surface area to volume ratio: the ratio between the surface area of an object, such as a fuel particle, to its volume. The smaller the particle, the more quickly it can become wet, dry out, or become heated to combustion temperature during a fire.

surface fire: fire that burns surface litter, dead woody fuels, other loose debris on the forest floor, and some small vegetation.

surface fuels: fuels that contact the surface of the ground, consisting of leaf and needle litter, dead branch material, downed logs, bark, tree cones, and low stature living plants.

survivors: plant species with established plants on the site that can vegetatively regenerate after the fire (Stickney 1986).

- T -

TAC: total available carbohydrates.

ten-hour timelag fuels: dead fuels consisting of roundwood 0.25 to 1.0 inches (0.6 to 2.5 cm) in diameter, estimated to reach 63 percent of equilibrium moisture content in ten hours.

thermoluminescence: a property of fired materials, such as ceramics, causing them to become luminous when gently heated again. Because this property decays at a known rate, the age of a ceramic artifact can be estimated by heating it and measuring the amount of phosphorescence.

tiller: new growth in a graminoid that originates from dormant axillary buds in the plant crown or on rhizomes (Dahl and Hyder 1977).

tillering: process of producing new grass growth from dormant axillary buds in the plant crown or on rhizomes (Dahl and Hyder 1977).

timelag: the time necessary for a fuel particle to lose or gain approximately 63 percent of the difference between its initial moisture content and its equilibrium moisture content.

torch: ignition and subsequent envelopment in flames, usually from bottom to top, of a tree or small group of trees.

total available carbohydrates (TAC): carbohydrates that are in a form that can be utilized as a readily available source of energy by a plant, including sugars, starch, dextrins, and fructosans (Smith et al. 1964 in Trlica 1977).

total fuel: all plant material, both living and dead, on a site.

trachea: in air breathing vertebrates, the tube that serves as the principal passage for conveying air to the lungs.

treatment: a procedure whose effect can be measured and compared with the effect of other procedures. Examples include a fall burned prescribed fire, an unburned "control", or an area burned with a specific ignition method or pattern.

- U -

underburning: prescribed burning in activity-created or natural fuels beneath a forest canopy, usually with the objective of preserving the dominant overstory trees.

utilization rates (limits): the proportion of the current year's forage production that is removed by grazing or browsing animals. It may refer to particular species or to the entire plant community and is usually expressed as a percentage.

- V -

vapor pressure: the contribution to total atmospheric pressure due to the presence of water molecules in the air (Schroeder and Buck 1970).

variable: any changing characteristic; in statistics, a measurable characteristic of an experimental unit.

variance: the sum of the squares of the deviates divided by one less than the total number of deviates; a measure which indicates how far away from the middle the statistics are; usually denoted by the lower case s^2. Variance is the standard deviation squared. In practice, it is easier to compute the variance, then take the square root to obtain the standard deviation. (See standard deviation.)

vegetative regeneration: development of new aboveground plants from surviving plant parts, such as by sprouting from a root crown or rhizomes. Even if plants form their own root system, they are still genetically the same as the parent plant (Zasada 1989).

vegetative reproduction: establishment of a new plant from a seed that is a genetically distinct individual (Zasada 1989).

vigor: a subjective assessment of the health of individual plants in similar site and growing conditions; or a more specific measure based upon a specific facet of growth, such as seed stalk or tiller production per plant or per unit area.

- W -

weight: as used in vegetation inventory and monitoring, the total biomass of living plants growing above the ground in a given area at a given time.

wildfire: a free burning and unwanted wildland fire requiring a suppression action.

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BIBLIOGRAPHY

Agee, J. K. 1993. Sitka spruce, coast redwood, and western hemlock forests, p. 187-225. IN Fire ecology of Pacific Northwest Forests. Island Press. Washington, DC.

Albini, Frank A. 1976. Estimating wildfire behavior and effects. USDA, For. Serv. Gen. Tech. Rep. INT-30. Intermt. For. and Range Exp. Sta., Ogden, UT. 92 p.

Allen, Arthur W. 1987. The relationship between habitat and furbearers, p. 164-179. IN Milan Novak, James A. Baker, Martyn E. Obbard, and Bruce Malloch (eds.). Wild furbearer management and conservation in North America. Ontario Trappers Assoc., Ontario, Canada.

American Micro Products, Inc. 1984. AMPI statistics library for the Hewlett-Packard HP-71B. AMPI, U.S.A. 217 p.

Anderson, Bruce A. 1985. Archaeological consideration for park and wilderness fire management planning, p. 145-148. IN James E. Lotan, Bruce M. Kilgore, William C. Fischer, and Robert W. Mutch (tech. coord.). Proc. - Symp. and workshop on wilderness fire. USDA, For. Serv. Gen. Tech. Rep. INT-182. Intermt. For. and Range Exp. Sta., Ogden, UT.

Anderson, Hal E. 1978. Graphic aids for field calculation of dead, down forest fuels. USDA, For. Serv. Gen. Tech. Rep. INT-45. Intermt. For. and Range Exp. Sta., Ogden, UT. 19 p.

Anderson, Hal E. 1982. Aids to determining fuel models for estimating fire behavior. USDA, For. Serv. Gen. Tech. Rep. INT-122. Intermt. For.

and Range Exp. Sta., Ogden, UT. 22 p.

Anderson, Hal. 1983. Burnout of large-sized woody fuels, p. 164-169. IN Proc. 17th Asilomar conf. on fire and blast effects of nuclear weapons. Lawrence Livermore Laboratory. Livermore, CA.

Anderson, Hal E. 1990. Moisture diffusivity and response time in fine forest fuels. Can. J. For. Res. 20: 315-325.

Anderson, Loren. 1983. Personal observation. Wildlife biologist. Salmon District. USDI, Bur. Land Manage. Salmon, ID.

Andrews, Patricia L. 1986. BEHAVE: Fire behavior prediction and fuel modeling system - BURN subsystem, part 1. USDA, For. Serv. Gen. Tech. Rep. INT-194. Intermt. Res. Sta., Ogden, UT. 130 p.

Andrews, Patricia L. and Larry S. Bradshaw. 1990. RXWINDOW: A program for defining windows of acceptable burning conditions for prescribed fire based on desired fire behavior. USDA, For. Serv. Gen. Tech. Rep. INT-273. Intermt. Res. Sta., Ogden, UT. 54 p.

Andrews, Patricia L. and Carolyn H. Chase. 1989. BEHAVE: Fire behavior prediction and fuel modeling system - BURN subsystem, part 2. USDA, For. Serv. Gen. Tech. Rep. INT-260. Intermt. Res. Sta., Ogden, UT. 93 p.

Armistead, John C. 1981. The Bandelier blowup. Amer. For. 87(10):29-62.

Arno, Stephen F. 1985. Ecological effects and management implications of Indian fires, p. 81-86. IN James E. Lotan, Bruce M. Kilgore, William C. Fischer, and Robert W. Mutch (tech. coord.). Proc. - Symp. and workshop on wilderness fire. USDA, For. Serv. Gen. Tech. Rep. INT-182. Intermt. For. and Range Exp. Sta., Ogden, UT.

Autenrieth, Robert, William Molini, and Clait Braun. 1982. Sage grouse management practices. Western States Sage Grouse Commit. Tech. Bull. 1. Twin Falls, ID. 42 p.

Barker, W. G. and W. B. Collins. 1963. The blueberry rhizome: In vitro culture. Can. J. Bot. 41:1325- 1329.

Barney, Milo A. and Neil C. Frischknecht. 1974. Vegetation changes following fire in the pinyon- juniper type of west-central Utah. J. Range Manage. 27(2):91-96.

Barrett, Stephen W. and Stephen F. Arno. 1982. Indian fires as an ecological influence in the Northern Rockies. J. Forest. 80:647-651.

Barro, Susan C. and Susan G. Conard. 1987. Use of ryegrass seeding as an emergency revegetation measure in chaparral ecosystems. USDA, For. Serv. Gen. Tech. Rep. PSW-102. Pacif. Southw. For. and Range Exp. Sta., Berkeley, CA. 12 p.

Bartels, Ronald, John D. Dell, Richard L. Knight, and Gail Schaefer. 1985. Dead and down woody material, p. 171-186. IN E. Reade Brown (ed.). Management of wildlife and fish habitats in forests of western Oregon and Washington. Part 1 - Chapter narratives. USDA, For. Serv. Publ. No. R6-F&WL-192-1985. Pacif. Northw. Reg., Portland, OR.

Batschelet, Edward. 1976. Introduction to mathematics for life scientists. Second edition. Springer- Verlag. New York. 643 p.

Beck, A. M. and Richard J. Vogl. 1972. The effects of spring burning on rodent populations in a brush prairie savannah. Mammalogy 53:336-346.

Bendell, J. F. 1974. Effects of fire on birds and mammals, p. 73-138. IN T. T. Kozlowski, and C. E. Ahlgren (eds.). Fire and ecosystems. Academic Press, New York.

Benson, Lyman. 1967. Plant classification. D.C. Heath and Company, Boston, MA. 688 p.

Bilderback, David. 1974. Personal conversation with Melanie Miller.

Black, C. A. (ed.). 1965. Methods of soil analysis. Part 1: Physical and mineralogical properties, including statistics of measurement and sampling, 770 p., and Part 2: Chemical and microbiological properties, 1572 p. Amer. Soc. Agron., Madison, WI.

Blackmarr, W. H. and William B. Flanner. 1968. Final Report.

Seasonal variation in moisture content of some common shrubs of the eastern North Carolina organic soils area. USDA, For. Serv. Rev. Draft FS-SE-2106-1-2. Southern For. Fire Lab. Southeast. For. Exp. Sta. 15 p. plus illus.

Blaisdell, J. P. and Walter F. Mueggler. 1956. Sprouting of bitterbrush following burning. Ecology 37(2):365-370.

Blaisdell, J. P., R. B. Murray, and E. D. McArthur. 1982. Managing Intermountain rangelands - Sagebrush-grass ranges. USDA, For. Serv. Gen. Tech. Rep. INT-134. Intermt. For. and Range Exp. Sta., Ogden, UT. 41 p.

Blaney, D.G. and G.E. Warrington. 1983. Estimating soil erosion using an erosion bridge. WSDG-TP- 00008. USDA, For. Serv. Watershed Develop. Group, Ft. Collins, CO.

Block, William M., Leonard A. Brennan, and R.J. Gutierrez. 1987. Evaluation of guild-indicator species for use in resource management. Environ. Manage. 11:265-269.

Blonski, Kenneth S. and John L. Schramel. 1981. Photo series for quantifying natural forest residues: Southern Cascades, Northern Sierra Nevada. USDA, For. Serv. Gen. Tech. Rep. PSW-56. Pacif. Southw. For. and Range Exp. Sta., Berkeley, CA. 145 p.

Bower, C. A. and L. V. Wilcox. 1965. Soluble salts, p. 933-951. IN C. A. Black (ed.). Methods of soil analysis. Part 2: Chemical and microbiological properties. Amer. Soc. Agron., Madison, WI.

Brackebusch, Arthur P. 1975. Gain and loss of moisture in large forest fuels. USDA, For. Serv. Res. Pap. INT-173. Intermt. For. and Range Exp. Sta., Ogden, UT. 50 p.

Bradshaw, Larry S. and Patricia L. Andrews. 1990. FCFAST: Fort Collins fire access software. Fire Management Notes 51(4):26-27.

Bradshaw, Larry S. and William Fischer. 1981a. A computer system for scheduling fire use. Part 1: The system. USDA, For. Serv. Gen. Tech. Rep. INT-91. Intermt. For. and Range Exp. Sta., Ogden, UT. 63 p.

Bradshaw, Larry S. and William Fischer. 1981b. A computer system for scheduling fire use. Part II: Computer terminal operator's manual. USDA, For. Serv. Gen. Tech. Rep. INT-100. Intermt. For. and Range Exp. Sta., Ogden, UT. 34 p.

Bradshaw, Larry S. and William Fischer. 1984. Computer programs for summarizing climatic data stored in the National Fire Weather Data Library. USDA, For. Serv. Gen. Tech. Rep. INT-164. Intermt. For. and Range Exp. Sta., Ogden, UT. 39 p.

Brand, David G. 1986. Competition induced changes in developmental features of planted Douglas-fir in southwestern British Columbia. Can. J. For. Res. 16:191-196.

Branson, F. A., G. F. Gifford, K. G. Renard, and R. F. Hadley. 1981. Rangeland hydrology. 2nd ed. Kendall/Hunt Pub. Co., Dubuque, IA. 340 p.

Britton, C. M. 1984. Personal conversation with Loren Anderson.

Britton, C. M., B. L. Karr, and F.A. Sneva. 1977. A technique for measuring rate of fire spread. J. Range Manage. 30(5):395-397.

Britton, Carlton M. and M. H. Ralphs. 1979. Use of fire as a management tool in sagebrush ecosystems, p. 101-109. IN The sagebrush ecosystem: A symposium. Utah State Univ., Logan.

Brown, Arthur A. and Kenneth P. Davis. 1973. Forest fire: Control and use. McGraw-Hill Book Company, New York. 686 p.

Brown, D. 1954. Methods of surveying and measuring vegetation. Commonwealth Bur. Pasture and Field Crops. Bull. 42. Hurley Berks, England. 233 p.

Brown, E. Reade (ed.). 1985. Management of wildlife and fish habitats in forests of western Oregon and Washington, parts 1 and 2. USDA, For. Serv. Publ. R6-F&WL-192. Pacif. Northw. Reg., Portland, OR. 332 p. and 302 p.

Brown, James K. 1974. Handbook for inventorying downed woody material. USDA, For. Serv. Gen. Tech. Rep. INT-116. Intermt. For and Range Exp. Sta., Ogden, UT. 24 p.

Brown, James K. 1975. Fire cycles and community dynamics in lodgepole pine forests, p. 429-456. IN D. M. Baumgartner (ed.). Management of lodgepole pine ecosystems. Coop. Extension Serv. Wash. State Univ., Pullman, WA.

Brown, James K. 1982. Fuel and fire behavior prediction in big sagebrush. USDA, For. Serv. Res. Pap. INT-290. Intermt. For and Range Exp. Sta., Ogden, UT. 10 p.

Brown, James K. 1987. Effects of fire on fuels. Lesson Plan. IN Managing Fire Effects. Boise Interag. Fire Center, Boise, ID. 26 p. and illus.

Brown, James K. 1989. Personal conversation with Loren Anderson.

Brown, James K., G. D. Booth, and D. G. Simmerman. 1989. Seasonal change in live fuel moisture of understory plants in western U.S. aspen, p. 406-412. IN D. C. MacIver, H. Auld, and R. Whitewood (eds.). Proc. 10th Conf. Fire and For. Meteorol. Environment Canada, Forestry Canada, Ottawa, ON, Canada.

Brown, James K., Michael A. Marsden, Kevin C. Ryan, and Elizabeth D. Reinhardt. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA, For. Serv. Res. Pap. INT-337. Intermt. For. and Range Exp. Sta., Ogden, UT. 23 p.

Brown, James K., Rick D. Oberheu, and Cameron M. Johnston. 1982. Handbook for inventorying surface fuels and biomass in the Interior West. USDA, For. Serv. Gen. Tech. Rep. INT-129. Intermt. For. and Range Exp. Sta., Ogden, UT. 48 p.

Brown, James K., Elizabeth D. Reinhardt, and William C. Fischer. 1991. Predicting duff and woody fuel consumption in northern Idaho prescribed fires. For. Sci. 37(6): 1550-1566.

Brown, James K. and Thomas E. See. 1981. Downed and dead woody fuel and biomass in the northern Rocky Mountains. USDA, For.

Serv. Gen. Tech. Rep. INT-117. Intermt. For. and Range Exp. Sta., Ogden, UT. 48 p.

Brown, James K. and Dennis G. Simmerman. 1986. Appraising fuels and flammability in western aspen: A prescribed fire guide. USDA, For. Serv. Gen. Tech. Rep. INT-205. Intermt. Res. Sta., Ogden, UT. 48 p.

Buckhouse, John C. and Gerald F. Gifford. 1976. Grazing and debris burning on pinyon-juniper sites -- Some chemical water quality implications. J. Range Manage. 29:299-301.

Buckman, Harry O. and Nyle C. Brady. 1966. The nature and properties of soils. A college text of edaphology. 6th Ed. The Macmillan Co., New York. 567 p.

Bunting, S. C. 1984. Personal conversation with Loren Anderson.

Bunting, Stephen C. 1985. Fire in sagebrush-grass ecosystems: Successional changes, p. 7-11. IN Ken Sanders and Jack Durham (eds.). Rangeland fire effects: A symposium. USDI, Bur. Land Manage., Idaho State Office, Boise.

Bunting, Stephen C., Bruce M. Kilgore, and Charles L. Bushey. 1987. Guidelines for prescribed burning sagebrush-grass rangelands in the Northern Great Basin. USDA, For. Serv. Gen. Tech. Rep. INT-231. Intermt. Res. Sta., Ogden, UT. 33 p.

Bunting, Stephen C., Leon F. Neuenschwander, and George Gruell. 1984. Ecology of antelope bitterbrush in the northern Rocky Mountains, p. 48-57. IN James E. Lotan and James K. Brown (eds.). Proc. - Fire's effects on wildlife habitat. USDA, For. Serv. Gen. Tech. Rep. INT-186. Intermt. For. and Range Exp. Sta., Ogden, UT.

Buol, S. W., F. D. Hole, and R. J. McCracken. 1973. Soil genesis and classification. The Iowa State Univ. Press. Ames, IA. 360 p.

Burgan, Robert E. 1993. Personal conversation with Melanie Miller.

Burgan, Robert E. and Richard C. Rothermel. 1984. BEHAVE: Fire behavior prediction and fuel modeling system - FUEL Subsystem. USDA, For. Serv. Gen. Tech. Rep. INT-167. Intermt. For. and Range

Exp. Sta., Ogden, UT. 126 p.

Burger, George V. 1979. Principles of wildlife management, p. 89-97. IN Richard D. Teague and Eugene Decker (eds.). Wildlife conservation: Principles and practices. The Wildlife Society, Washington, D.C.

Burgh, Robert F. 1960. Potsherds and forest fires in the Pueblo country. Plateau 33:54-56.

Byram, George M. 1959. Combustion of forest fuels, p. 61-89. IN Davis, Kenneth P. Forest fire: Control and use. McGraw-Hill Book Company, Inc. New York.

Caldwell, M. M., J. H. Richards, D. A. Johnson, and R. S. Dzurec. 1981. Coping with herbivory: Photosynthetic capacity and resource allocation in two semiarid *Agropyron* bunchgrasses. Oecologia (Berlin) 50:14-24.

Campbell, T. M., III. 1979. Short-term effects of timber harvests on pine marten ecology. M.S. Thesis, Colo. St. Univ., Ft. Collins. 76 p.

Carpenter, L. H. 1976. Nitrogen-herbicide effects on sagebrush deer range. Ph.D. Thesis, Colo. St. Univ., Ft. Collins. 159 p.

Chambers, Jeanne C. and Ray W. Brown. 1983. Methods for vegetation sampling and analysis on revegetated mined lands. USDA, For. Serv. Gen. Tech. Rep. INT-151. Intermt. For. and Range Exp. Sta., Ogden, UT. 37 p.

Chandler, Craig, Phillip Cheney, Philip Thomas, Louis Trabaud, and Dave Williams. 1983. Fire in forestry, Volume I: Forest fire behavior and effects. John Wiley & Sons, New York. 450 p.

Chase, Alston. 1988. Scientific breakdown: The cultural weakness behind our ecological failures. Outside (Nov.):45-46.

Christensen, Norman L. and Cornelius H. Muller. 1975a. Relative importance of factors controlling germination and seedling survival in *Adenostoma* chaparral. Amer. Midl. Natur. 93(1):71-78.

Christensen, Norman L. and Cornelius H. Muller. 1975b. Effects of fire on factors controlling plant growth in *Adenostoma* chaparral. Ecolog. Monog. 45:29-55.

Chrosciewicz, Z. 1986. Foliar moisture content variations in four coniferous tree species of central Alberta. Can. J. For. Res. 16:157-162.

Clark, Robert G. 1986. Personal conversation with Melanie Miller.

Clark, Robert G. 1989. Personal conversation with Melanie Miller.

Cohen, Warren B., Philip N. Omi, and Merrill R. Kaufmann. 1990. Heating-related water transport to intact lodgepole pine branches. For. Sci. 36(2): 246-254.

Conrad, C. Eugene and Charles E. Poulton. 1966. Effect of wildfire on Idaho fescue and bluebunch wheatgrass. J. Range Manage. 19:138-141.

Cook, C. Wayne. 1966a. Carbohydrate reserves in plants. Utah Agr. Exp. Sta. Resour. Ser. No. 31. 47 p.

Cook, C. Wayne. 1966b. The role of carbohydrate reserves in managing range plants. Utah Agr. Exp. Sta. Mimeo Ser. 499. 11 p.

Cook, C. Wayne and James Stubbendieck (eds.). 1986. Range research: Basic problems and techniques. Soc. Range Manage., Denver, CO. 317 p.

Cooperrider, A. Y., R. J. Boyd, and H. R. Stuart (eds.). 1986. Inventory and monitoring of wildlife habitat. USDI, Bur. Land Manage., Service Center, Denver, CO. 858 p.

Countryman, Clive M. 1972. The fire environment concept. USDA, For. Serv. Pacif. Southw. For. and Range Exp. Sta., Berkeley, CA.

Countryman, Clive M. 1976. Heat--It's role in wildland fire--Part 3. Heat conduction and wildland fire. USDA, For. Serv. Pacif. Southw. For. and Range Exp. Sta., Berkeley, CA. 12 p.

Countryman, Clive M. and William M. Dean. 1979. Measuring moisture content in living chaparral: A field user's manual. USDA, Forest Service. Gen. Tech. Rep. PSW-36. Pacif. Southw. For. and Range Exp. Sta., Berkeley, CA. 27 p.

Countryman, Clive M. and Charles W. Philpot. 1970. Physical characteristics of chamise as a wildland fuel. USDA, For. Serv. Res. Pap. PSW-66. Pacif. Southw. For. and Range Exp. Sta., Berkeley, CA. 16 p.

Dahl, B. E. and D. N. Hyder. 1977. Developmental morphology and management implications, p. 257- 290. IN Ronald E. Sosebee, and 9 others. Rangeland plant physiology. Soc. for Range Manage. Denver, CO.

Dasmann, Raymond F. 1978. Wildlife and ecosystems, p. 18-27. IN H. P. Brokaw (ed.). Wildlife and America. Counc. Environ. Qual., Washington, D.C.

Daubenmire, Rexford. 1959. A canopy-coverage method of vegetational analysis. Northw. Science 33:43-64.

Daubenmire, Rexford 1968a. Ecology of fire in grasslands. Adv. Ecol. Res. 5:209-266.

Daubenmire, Rexford. 1968b. Plant communities. A textbook of plant synecology. Harper & Row. New York. 300 p.

Daubenmire, Rexford. 1975. Plant succession on abandoned fields, and fire influences in a steppe area in southeastern Washington. Northw. Sci. 49(1):36-48.

Davis, Edwin A. 1984. Conversion of Arizona chaparral to grass increases water yield and nitrate loss. Water Resour. Res. 20:1643-1649.

Davis, Kenneth P. 1959. Forest fire: Control and use. McGraw-Hill Book Company, Inc. New York. 584 p.

Dealy, Edward J., Donavin A. Leckenby, and Diane M. Concannon. 1981. Plant communities and their importance to wildlife. 66 p. IN Wildlife habitats in managed rangelands - The Great Basin of southeastern Oregon. USDA, For. Serv. Gen. Tech. Rep. PNW-120.

Pacif. Northw. For. and Range Exp. Sta., Portland, OR.

DeBano, Leonard F. 1969a. Observations on water repellent soils in the western United States, p.7- 29. IN Proc. symp. on water repellent soils. Univ. Calif., Riverside.

DeBano, Leonard F. 1969b. Water repellent soils: A worldwide concern in management of soil and vegetation. Agric. Sci. Rev. 7:11-18.

DeBano, Leonard F. 1977. Fire's effect on physical and chemical properties of chaparral soils, p. 65- 74. IN Harold A. Mooney and C. Eugene Conrad (eds.). Proc. symp. on environmental consequences of fire and fuel management in Mediterranean ecosystems. USDA, For. Serv. Gen. Tech. Rep. WO-3. Washington, D.C.

DeBano, Leonard F. 1979. Effects of fire on soil properties, p. 109-118. IN California forest soils. Univ. Calif. Div. Agric. Sci. Pub. 4094, Berkeley, CA.

DeBano, Leonard F. 1981. Water repellent soils: A state-of-the art. USDA, For. Serv. Gen. Tech. Rep. PSW-46. Pacif. Southw. For. and Range Exp. Sta., Berkeley, CA. 21 p.

DeByle, Norbert V. 1988a. Personal conversation with Melanie Miller.

DeByle, Norbert V. 1988b. Personal conversation with Loren Anderson.

DeByle, Norbert V. and Paul E. Packer. 1972. Plant nutrient and soil losses in overland flow from burned forest clearcuts, p. 296-307. IN Watersheds in transition. Amer. Water Resour. Assoc. and Colo. State Univ., Ft. Collins.

Deeming, John E., Robert E. Burgan, and Jack D. Cohen. 1978. The National Fire-Danger Rating System - 1978. USDA, For. Serv. Gen. Tech. Rep. INT-39. Intermt. For. and Range Exp. Sta., Ogden, UT. 63 p.

Dell, John D. and Charles W. Philpot. 1965. Variations in the moisture content of several fuel size components of live and dead chamise. USDA, For. Serv. Res. Note PSW-83. Pacif. Southw. For. and Range

Exp. Sta., Berkeley, CA. 7 p.

Dixon, W. J. (ed.). 1985. BMDP statistical software. Univ. Calif. Press, Berkeley.

Dost, F. N. 1990. Acute toxicology of components of vegetation smoke. Reviews of Environmental Contamination and Toxicology Vol. 119:1-46.

Dubos, Rene. 1972. A God within. Charles Scribner's and Sons. p. 155-210.

Dyksterhuis, E. J. 1958. Range conservation as based on sites and condition classes. J. Soil and Water Conserv. Vol. 13, No. 4. 1 p.

Dyrness, C. T. and Rodney A. Norum. 1983. The effects of experimental fires on black spruce forest floors in interior Alaska. Can. J. For. Res. 13(5):879-893.

EPA. 1976. Quality criteria for water. U.S. Environ. Prot. Agency, Washington, D.C. 256 p.

EPA. 1979. Methods for chemical analysis of water and wastes. EPA-600 4-79-020. U.S. Environ. Prot. Agency, Office of Res. and Develop., Cincinnati, OH. 460 p.

Eshelman, Kris, Shirley Hudson, Bob Mitchell, Mike Pellant, and Kay Thomas. 1986. The lighter side of statistics. (Revised). USDI, Bur. Land Manage., Service Center, Denver, CO. 36 p.

Evans, Raymond A. 1988. Management of pinyon-juniper woodlands. USDA, For. Serv. Gen. Tech. Rep. INT-249. Intermt. Res. Sta., Ogden, UT. 34 p.

Everett, Richard L. 1987a. Allelopathic effects of pinyon and juniper litter on emergence and growth of herbaceous species, p. 62-67. IN Gary W. Frasier and Raymond A. Evans (eds.). Proc. - Symp. seed and seedbed ecology of rangeland plants. USDA, Agric. Res. Serv.

Everett, Richard L. 1987b. Plant response to fire in the pinyon-juniper zone, p. 152-157. IN Richard L. Everett (comp.). Proc. - Pinyon-juniper conf. USDA, For. Serv. Gen. Tech. Rep. INT-215. Intermt. Res. Sta., Ogden, UT.

Fagen, Robert. 1988. Population effects of habitat change. J. Wildl. Manage. 52:41-46.

Farnsworth, R. B., E. M. Romney, and A. Wallace. 1978. Nitrogen fixation by microfloral-higher plant associations in arid and semiarid environments, p. 17-19. IN Neil E. West and John J. Skujins (eds.). Nitrogen in desert ecosystems. US/IBP Synthesis Ser. 9. Dowden, Hutchinson, and Ross, Inc., Stroudsburg, PA.

Feller, M. C. and J. P. Kimmins. 1984. Effects of clearcutting and slash burning on streamwater chemistry and watershed nutrient budgets in southwestern British Columbia. Water Resour. Res. 20:29-40.

Ferguson, Robert. 1988. Personal conversation with Melanie Miller.

Finklin, Arnold I. and William C. Fischer. 1990. Weather station handbook--An interagency guide for wildland managers. Natl. Wildf. Coord. Grp. NFES No. 1140. PMS No. 426-2. Natl. Interag. Fire Center, Boise, ID. 237 p.

Fischer, William C. 1981a. Photo guides for appraising downed woody fuels in Montana forests: How they were made. USDA, For. Serv. Res. Note INT-299. Intermt. For. and Range Exp. Sta., Ogden, UT. 12 p.

Fischer, William C. 1981b. Photo guide for appraising downed woody fuels in Montana forests: Grand fir - larch - Douglas-fir; western hemlock - western redcedar; and western redcedar cover types. USDA, For. Serv. Gen. Tech. Rep. INT-96. Intermt. For. and Range Exp. Sta., Ogden, UT. 53 p.

Fischer, William C. 1981c. Photo guide for appraising downed woody fuels in Montana forests: Interior ponderosa pine; ponderosa pine - larch - Douglas-fir; larch - Douglas-fir; and interior Douglas-fir cover types. USDA, For. Serv. Gen. Tech. Rep. INT-97. Intermt. For. and Range Exp. Sta., Ogden, UT. 133 p.

Fischer, William C. 1981d. Photo guide for appraising downed woody fuels in Montana forests: Lodgepole pine, and Engelmann spruce -

subalpine fir cover types. USDA, For. Serv. Gen. Tech. Rep. INT-98. Intermt. For. and Range Exp. Sta., Ogden, UT. 143 p.

Flinn, Marguerite A. and Ross W. Wein. 1977. Depth of underground plant organs and theoretical survival during fire. Can J. Bot. 55:2550-2554.

Floyd, Donald A. and Jay E. Anderson. 1987. A comparison of three methods for estimating plant cover. J. Ecol. 75:221-228.

Ford-Robertson, F. C. (ed.). 1971. Terminology of forest science technology practice and products: English-language version. Soc. Amer. Forest. Multilingual For. Term. Ser. 1., Washington, D.C.

Fosberg, Michael. 1975. Heat and water vapor flux in conifer forest litter and duff: A theoretical model. USDA, For. Serv. Res. Pap. RM-152. Rocky Mt. For. and Range Exp. Sta., Ft. Collins, CO. 23 p.

Frandsen, William H. 1987. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. Can J. For. Res. 17: 1540-1544.

Frandsen, William H. 1993. Personal conversation with Melanie Miller. January 28, 1993.

Frandsen, W. H., R. H. Hungerford, and K. C. Ryan. 1993. Heat transfer into the duff and organic soil. Progress Report. Cooperative Agreement 14-48-0009-92-962 DCN:98210-2-3927. USDI, Fish and Wildl. Serv., and USDA, For. Serv. 26 p.

Frandsen, William H. and Kevin C. Ryan. 1986. Soil moisture reduces belowground heat flux and soil temperatures under a burning fuel pile. Can. J. For. Res. 16:244-248.

Freese, Frank. 1962. Elementary forest sampling. USDA, Agric. Handbk. 232. 91 p. (1)

Freese, Frank. 1967. Elementary statistical methods for foresters. USDA, Agric. Handbk. 317. 87 p. [1]

Frischknecht, Neil C. 1978. Effects of grazing, climate, fire, and other disturbances on long-term productivity of sagebrush-grass ranges, p. 633-735. IN Proc. First Internatl. Rangeland Congress.

Furman, R. William. 1979. Using fire weather data in prescribed fire planning: Two computer programs. USDA, For. Serv. Gen. Tech. Rep. RM-63. Rocky Mt. For. and Range Exp. Sta., Ft. Collins, CO. 11 p.

Gardner, Walter H. 1965. Water content, p. 82-127. IN C. A. Black (ed.). Methods of soil analysis. Part 1: Physical and mineralogical properties, including statistics of measurement and sampling. Amer. Soc. Agron., Madison, WI.

Gary, Howard L. 1971. Seasonal and diurnal changes in moisture contents and water deficits of Engelmann spruce needles. Bot. Gaz. 132(4):327-332.

Geier, A. R. and Louis B. Best. 1980. Habitat selection by small mammals of riparian communities: Evaluating effects of habitat alterations. J. Wildl. Manage. 44:16-24.

German, Stephen C. 1988. Initial Attack Management System (IAMS). Information package. Bur. Land Manage., Div. Inform. Systems Manage. Boise Interag. Fire Center, ID. 33 p.

Germano, David J. and David N. Lawhead. 1986. Species diversity and habitat complexity: Does vegetation organize vertebrate communities in the Great Basin? Great Basin Natur. 46:711-720.

Getz, L. L. 1968. Influence of water balance and microclimate on the local distribution of the red-back vole and white-footed mouse. Ecology 49:276-280.

Golterman, H. L. and R. S. Clymo. 1969. Methods for chemical analysis of fresh waters. IBP Handbk. 8. Blackwell Sci. Pub., Oxford, GB.

Gratkowski, H. 1973. Pregermination treatments for redstem ceanothus seed. USDA, For. Serv. Res. Pap. PNW-156. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 10 p.

Graul, Walter D. and G. C. Miller. 1984. Strengthening ecosystem management approaches. Wildl. Soc. Bull. 12:282-289

Greig-Smith, P. 1983. Quantitative plant ecology. 3rd ed. Univ. Calif. Press, Berkeley. 359 p.

Gruell, George E. 1985. Indian fires in the Interior West: A widespread influence, p. 68-74. IN James E. Lotan, Bruce M. Kilgore, William C. Fischer, and Robert W. Mutch (tech. coord.). Proc. - Symp. and workshop on wilderness fire. USDA, For. Serv. Gen. Tech. Rep. INT-182. Intermt. For. and Range Exp. Sta., Ogden, UT.

Haeussler, S. and D. Coates. 1986. Autecological characteristics of selected species that compete with conifers in British Columbia: A literature review. B.C. Ministry of Forests and Lands. FRDA Rep. 001. Victoria, BC, Canada. 180 p.

Hall, Frederick C. 1985. Management practices and options, 16 p. IN Wildlife habitats in managed rangelands - The Great Basin of southeastern Oregon. USDA, For. Serv. Gen. Tech. Rep. PNW-189. Pacif. Northw. For. and Range Exp. Sta., Portland, OR.

Hanks, R. J. and G. L. Ashcroft. 1980. Applied soil physics. Springer-Verlag, Berlin. 159 p.

Hansen, James D. 1986. Comparison of insects from burned and unburned areas after range fire. Great Basin Natur. 46:721-727.

Hanson, Harold Christian. 1962. Dictionary of ecology. Philos. Libr., New York. 382 p.

Hardy, Colin. 1990. Personal conversation with Larry Mahaffey.

Hardy, R. 1945. Breeding birds of the pygmy conifers in the Book Cliff regions of eastern Utah. Auk 62:523-542.

Harniss, Roy O. and Robert B. Murray. 1973. Thirty years of vegetal change following burning of sagebrush-grass range. J. Range Manage. 26(5):322-325.

Harper, Kimball T., Fred J. Wagstaff, and Lynn M. Kunzler. 1985. Biology and management of the Gambel oak vegetative type: A literature review. USDA, For. Serv. Gen. Tech. Rep. INT-179. Intermt. For. and Range Exp. Sta., Ogden, UT. 31 p.

Harrington, Michael G. 1987. Predicting reduction of natural fuels by prescribed burning under ponderosa pine in southeastern Arizona. USDA, For. Serv. Res. Note RM-472. Rocky Mt. For. and Range Exp. Sta., Ft. Collins, CO. 4 p.

Harrington, Michael G. and Stephen S. Sackett. 1990. Using fire as a management tool in southwestern ponderosa pine, p. 122-133. IN J. S. Krammes (tech. coord.). Effects of fire management of southwestern natural resources. Proc. of the symp. USDA, For. Serv. Gen. Tech. Rep. RM-191. Rocky Mt. For. and Range Exp. Sta., Ft. Collins, CO.

Harris, Grant A. 1977. Root phenology as a factor of competition among grass seedlings. J. Range Manage. 30(3):172-177.

Harris, L. D. and W. R. Marion. 1981. Forest stand scheduling for wildlife in the mutiple-use forest, p. 209-214. IN Proc. conf. of the Soc. of Amer. Foresters. Orlando, FL.

Hartford, R. A. 1989. Smoldering combustion limits in peat as influenced by moisture, mineral content, and organic bulk density, p. 282-286. IN D. H. MacIver, H. Auld, and R. Whitewood (eds.). Proc. 10th Conf. Fire and For. Meteorol. Environment Canada, Forestry Canada, Ottawa, ON, Canada.

Hartford, Robert A. 1993. Personal conversation with Melanie Miller.

Hartford, Roberta A. and William H. Frandsen. 1992. When it's hot, it's hot . . . or maybe it's not. (Surface flaming may not portend extensive soil heating). Intl. J. Wildl. Fire 2(3):139-144.

Hartford, Roberta A. and Richard C. Rothermel. 1991. Fuel moisture as measured and predicted during the 1988 fires in Yellowstone Park. USDA, For. Serv. Res. Note INT-396. Intermt. Res. Sta., Ogden, UT. 7 p.

Harvey, Alan E., Martin F. Jurgensen, Michael J. Larsen, and Russell T. Graham. 1987. Decaying organic materials and soil quality in the inland Northwest: A management opportunity. USDA, For. Serv.

Gen. Tech. Rep. INT-225. Intermt. Res. Sta., Ogden, UT. 15 p.

Harvey, Alan E., Martin F. Jurgensen, Michael J. Larsen, and Joyce A. Schlieter. 1986. Distribution of active ectomycorrhizal short roots in forest soils of the Inland Northwest: Effects of site and disturbance. USDA, For. Serv. Res. Pap. INT-374. Intermt. Res. Sta., Ogden, UT. 8 p.

Haslem, Jack. 1986. Rangeland burning for maximum returns, p. 203-208. IN Proc. fire management: The challenge of protection and use. Dept. For. Resour., Utah. State Univ., Logan, UT.

Hatton, Thomas J., Neil R. Viney, E. A. Catchpole, Neville J. De Mestre. 1988. The influence of soil moisture on eucalyptus leaf litter moisture. For. Sci. 34(2): 292-301.

Haupt, H. F. 1979. Local climatic and hydrologic consequences of creating openings in climax timber of north Idaho. USDA, For. Serv. Res. Pap. INT-223. Intermt. For. and Range Exp. Sta., Ogden, UT. 43 p.

Hays, Robert L., Cliff Summers, and William Seitz. 1981. Estimating wildlife habitat variables. USDI, Fish and Wildl. Serv. FWS/OBS-81-47. Washington, D.C. 111 p.

Heilman, P. E. 1966. Change in distribution and availability of nitrogen with forest succession on north slopes in interior Alaska. Ecology 47:826-831.

Heilman, P. E. 1968. Relationship of availability of phosphorus and cations to forest succession and bog formation in interior Alaska. Ecology 49(2):331-336.

Helvey, J. D., A. R. Tiedemann, and T. D. Anderson. 1985. Plant nutrient losses by soil erosion and mass movement after wildfire. J. Soil, Water Conserv. 40:168-173.

Hem, John D. 1970. Study and interpretation of the chemical characteristics of natural water. Water Supply Pap. 1473. USDI, Geol. Surv., Washington, D.C. 363 p.

Hermann, Sharon M., Ronald A. Phernetton, Allen Carter, and Tony Gooch. 1991. Fire and vegetation in peat-based marshes of the Coastal Plain: Examples from the Okefenokee and Great Dismal Swamps, p. 217-234. IN High intensity fire in wildlands: Management challenges and options. Proc. 17th Tall Timbers Fire Ecol. Conf. Tall Timbers Res. Sta. Tallahassee, FL.

Hibbert, Alden R. 1983. Water yield improvement potential by vegetation management on western rangelands. Water Resour. Bull. 19:375-381.

Hobbs, N. T. and R. W. Spowart. 1984. Effects of prescribed fire on nutrition of mountain sheep and mule deer during winter and spring. J. Wildl. Manage. 48:551-560.

Hobbs, N. Thompson. 1989. Linking energy balance to survival in mule deer: Development and test of a simulation model. J. Wildl. Manage. Wildl. Monogr. 101. 39 p.

Holechek, Jerry L. 1988. An approach for setting the stocking rate. Rangelands 10(1):10-14.

Huber, D. M., H. L. Warren, D. W. Nelson, and C. Y. Tsai. 1977. Nitrification inhibitors - New tools for food production. BioScience 27:523-529.

Huff, Mark H., James K. Agee, and David A. Manuwal. 1984. Postfire succession of avifauna in the Olympic Mountains, Washington, p. 8-15. IN James E. Lotan and James K. Brown (eds.). Proc. - Fire's effects on wildlife habitat. USDA, For. Serv. Gen. Tech. Rep. INT-186. Intermt. For. and Range Exp. Sta., Ogden, UT.

Hungerford, Roger. 1989. Modeling the downward heat pulse from fire in soils and in plant tissue, p. 148-154. IN D. C. MacIver, H. Auld, and R. Whitewood (eds.). Proc. - 10th Conf. on Fire and Forest Meteorol. Environment Canada, Forestry Canada, Ottawa, ON, Canada.

Hutchings, Selar S. and Jack E. Schmautz. 1969. A field test of the relative-weight estimate method for determining herbage production. J. Range Manage. 22(6): 408-411.

Hutchison, B. A. 1965. Snow accumulation and disappearance influenced by big sagebrush. USDA, For. Serv. Res. Note RM-46. Rocky Mt. For. and Range Exp. Sta., Ft. Collins, CO.

James, Susanne. 1984. Lignotubers and burls - Their structure, function and ecological significance in Mediterranean ecosystems. Bot. Rev. 50(3):225-266.

Johansen, Ragnar, John Deeming, Mike Long, and Darold Ward. 1985. Chapter II. Smoke production characteristics and effects, p. 5-10. IN Prescribed fire smoke management guide. National Wildf. Coord. Grp. Prescr. Fire and Fire Effects Working Team. NFES No. 1279.

Johnsgard, P. A. and W. H. Rickard. 1957. The relationship of spring bird distribution to vegetative mosaic in southern Washington. Ecology 38:171-174.

Jones, Anne T. and Robert C. Euler. 1986. Effects of forest fires on archaeological resources at Grand Canyon National Park. N. Amer. Archaeol. 7:243-254.

Jones, John R. 1985. Distribution, p. 9-18. IN Norbert V. DeByle and Robert P. Winokur (eds.). Aspen: Ecology and management in the western United States. USDA, For. Serv. Gen. Tech. Rep. RM-119. Rocky Mt. For. and Range Exp. Sta., Ft. Collins, CO.

Jones, John R. and Norbert V. DeByle. 1985. Fire, p. 77-81. IN Norbert V. DeByle and Robert P. Winokur (eds.). Aspen: Ecology and management in the western United States. USDA, For. Serv. Gen. Tech. Rep. RM-119. Rocky Mt. For. and Range Exp. Sta., Ft. Collins, CO.

Keane, Robert E., James K. Brown, Elizabeth D. Reinhardt, and Kevin C. Ryan. 1990. Predicting first order fire effects in the United States. Compiler 8(4):11-15.

Keeley, Jon E. 1987. Role of fire in seed germination of woody taxa in California chaparral. Ecology 68(2):434-443.

Kelleyhouse, David G. 1980. Fire/wildlife relations in Alaska. Unpub. manuscript. Alaska Dept. of Fish and Game, Fairbanks. 19 p.

Kelly, Roger E. and Jim Mayberry. 1980. Trial by fire: Effects of NPS burn programs upon archaeological resources, p. 603-610. IN Proc. second conf. on scientific research in the Natl. Parks, Volume 1. USDI, Nat. Park Serv., West. Reg., San Francisco, CA.

Kender, Walter J. 1967. Rhizome development in the lowbush blueberry as influenced by temperature and photoperiod. Am. Soc. Hort. Sci. 90:144-148.

Kindschy, Robert R. 1986. Rangeland vegetative succession - Implications to wildlife. Rangelands 8:157-159.

Kirby, Ronald E., Stephen J. Lewis, and Terry N. Sexon. 1988. Fire in North American wetland ecosystems and fire-wildlife relations: An annotated bibliography. USDI, Fish Wildl. Serv. Bio. Rep. 88(1). Washington, D.C.

Knopf, Fritz L., James A. Sedgewick, and Richard W. Cannon. 1988. Guild structure of a riparian avifauna relative to seasonal cattle grazing. J. Wildl. Manage. 52:280-290.

Koski, Wayne H. and William C. Fischer. 1979. Photo series for appraising thinning slash in north Idaho: Western hemlock, grand fir, and western redcedar timber types. USDA, For. Serv. Gen. Tech. Rep. INT-46. Intermt. For. and Range Exp. Sta., Ogden, UT. 50 p.

Krammes, J. S. and J. Osborn. 1969. Water-repellent soils and wetting agents as factors influencing erosion, p. 177-187. IN L. F. DeBano and J. Letey (eds.). Proc. symp. on water-repellent soils. Univ. Calif., Riverside.

Lancaster, James W. 1970. Timelag useful in fire danger rating. Fire Control Notes 32(3): 6-8, 10.

Lance, J. C., S. C. McIntyre, J. W. Naney, and S. S. Rousseva. 1986. Measuring sediment movement at low erosion rates using Cesium-137. J. Soil Sci. Soc. of Amer. Vol. 50: 1303-1309.

Larson, L. L. and P. A. Larson. 1988. Historic landscape restoration: Views from 3 angles. Park Sci. 8(3):6-9. USDI, Natl. Park Serv., Washington, D.C.

Lawrence, G. E. 1966. Ecology of vertebrate animals in relation to chaparral fire on the Sierra Nevada foothills. Ecology 47:278-291.

Laycock, W. A. 1979. Management of sagebrush. Rangelands 1: 207-210.

Leege, Thomas A. 1968. Prescribed burning for elk in northern Idaho, p. 235-253. IN Proc. Tall Timbers Fire Ecol. Conf. No. 8. Tall Timbers Res. Sta., Tallahassee, FL.

Leege, Thomas A. and William O. Hickey. 1971. Sprouting of northern Idaho shrubs after prescribed burning. J. Wildl. Manage. 35:508-515.

Leopold, A. S. and F. F. Darling. 1953. Effects of land use on moose and caribou in Alaska. Trans. North. Amer. Wildl. Conf. 18:553-562.

Lewis, Henry T. 1973. Patterns of Indian burning in California: Ecology and ethnohistory. Ballena Press Anthropol. Papers, No. 1. Ramona, CA. 101 p.

Lewis, Henry T. 1985. Why Indians burned: Specific versus general reasons, p. 75-80. IN James E. Lotan, Bruce M. Kilgore, William C. Fischer, and Robert W. Mutch (tech. coord.). Proc. - Symp. and workshop on wilderness fire. USDA, For. Serv. Gen. Tech. Rep. INT-182. Intermt. For. and Range Exp. Sta., Ogden, UT.

Littke, W. R. and R. I. Gara. 1986. Decay of fire-damaged lodgepole pine in south-central Oregon. For. Ecol. & Manage. 17:279-287.

Little, Susan N., Roger D. Ottmar, and Janet L. Ohmann. 1986. Predicting duff consumption from prescribed burns on conifer clearcuts in western Oregon and western Washington. USDA, For. Serv. Res. Pap. PNW-362. Pacif. Northw. Res. Sta., Portland, OR.

29 p.

Little, Thomas M. and F. Jackson Hills. 1978. Agricultural experimentation. John Wiley & Sons, New York. 350 p.

Loomis, Robert M. and Richard W. Blank. 1981. Summer moisture content of some northern lower Michigan understory plants. USDA, For. Serv. Res. Note NC-263. N. Central For. Exp. Sta., St. Paul, MN. 4 p.

Lotan, James E. 1976. Cone serotiny - fire relationships in lodgepole pine, p. 267-278. IN Proc. Tall Timbers Fire Ecol. Conf. No. 14. Tall Timbers Res. Sta., Tallahassee, FL.

Lyon, J. G., J. F. McCarthy, and J. T. Heinen. 1986. Video digitation of aerial photographs for measurement of wind erosion damage on converted rangeland. Photogram. Enginrg. and Remote Sensing 52(3): 373-377.

Lyon, L. Jack, Hewlette S. Crawford, Eugene Czuhai, Richard L. Fredricksen, Richard F. Harlow, Louis J. Metz, and Henry A. Pearson. 1978. Effects of fire on fauna: A state-of-knowledge review. USDA, For. Serv. Gen. Tech. Rep. WO-6. Washington, D.C. 41 p.

Lyon, L. Jack and John M. Marzluff. 1984. Fire's effects on a small bird population, p. 16-22. IN James E. Lotan and James K. Brown (eds.). Proc .- Fire's effects on wildlife habitat. USDA, For. Serv. Gen. Tech. Rep. INT-186. Intermt. For. and Range Exp. Sta., Ogden, UT.

MacMahon, J. A. 1980. Ecosystems over time: Succession and other types of change, p. 27-58. IN R. H. Waring (ed.). Forests: Fresh perspectives from ecosystem analysis. Oregon St. Univ. Press, Corvallis.

Main, William A., Robert G. Straub, and Donna M. Pannanen. 1988. FIREFAMILY 1988. USDA, For. Serv. Gen. Tech. Rep. NC-138. N. Central For. Exp. Sta., St. Paul, MN. 35 p.

Mandeville, M. D. 1973. A consideration of the thermal pre-treatment of chert. Plains Anthropol. 18:177-202.

Martin, Robert E. 1963. A basic approach to fire injury of tree stems, p. 151-162. IN Proc. Tall Timbers Fire Ecol. Conf. No. 2. Tall Timbers Res. Sta., Tallahassee, FL.

Martin, Robert E., Hal E. Anderson, William D. Boyer, John H.

Dieterich, Stanley N. Hirsch, Von J. Johnson, and W. Henry McNab. 1979. Effects of fire on fuels. A state-of-knowledge review. USDA, For. Serv. Gen. Tech. Rep. WO-13. 64 p.

Martin, Robert E., David W. Frewing, and James L. McClanahan. 1981. Average biomass of four Northwest shrubs by fuel size class and crown cover. USDA, For. Serv. Res. Note PNW-74. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 6 p.

Maser, Chris and Jay S. Gashwiler. 1978. Interrelationships of wildlife and western juniper, p. 37-82. IN Robert E. Martin, J. Edward Dealy, and David L. Caraher (eds.). Proc. - Western juniper ecology and management workshop. USDA, For. Serv. Gen. Tech. Rep. PNW-74. Pacif. Northw. For. and Range Exp. Sta., Portland, OR.

Maser, Chris, Jack Ward Thomas, and Ralph G. Anderson. 1984. The relationship of terrestrial vertebrates to plant communities, part 1 and 2. 25 p. and 237 p. IN Wildlife habitats in managed rangelands - The Great Basin of southeastern Oregon. USDA, For. Serv. Gen. Tech. Rep. PNW-172. Pacif. Northw. For. and Range Exp. Sta., Portand, OR.

Mathews, Ed, Lee Lavdas, Larry Mahaffey, Tom Nichols, Dave Sandberg, and Mike Ziolko. 1985. Chapter III. Smoke management, p. 11-18. IN Prescribed fire smoke management guide. Natl. Wildf. Coord. Grp. Prescr. Fire and Fire Effects Working Team. NFES No. 1279.

Maxwell, Wayne G. and Franklin R. Ward. 1976a. Photo series for quantifying forest residues in the coastal Douglas-fir - hemlock type; coastal Douglas-fir - hardwood type. USDA, For. Serv. Gen. Tech. Rep. PNW-51. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 103 p.

Maxwell, Wayne G. and Franklin R. Ward. 1976b. Photo series for quantifying forest residues in the ponderosa pine type; ponderosa pine and associated species type; lodgepole pine type. USDA, For. Serv. Gen. Tech. Rep. PNW-52. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 73 p.

Maxwell, Wayne G. and Franklin R. Ward. 1979. Photo series for quantifying forest residues in the Sierra mixed conifer type, Sierra true fir type. USDA, For. Serv. Gen. Tech. Rep. PNW-95. Pacif. Northw. For. and Range Exp. Sta., Portland, OR.

Maxwell, Wayne G. and Franklin R. Ward. 1980. Photo series for quantifying natural forest residues in common vegetation types of the Pacific Northwest. USDA, For. Serv. Gen. Tech. Rep. PNW-105. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 229 p.

McAdoo, J. Kent, William S. Longland, and Raymond A. Evans. 1989. Nongame bird community responses to sagebrush invasion of crested wheatgrass seedings. J. Range Manage. 53:494-502.

McCammon, Bruce P. 1976. Snowpack influences on dead fuel moisture. For. Sci. 22(3): 323-328.

McConnell, B. R. and G. A. Garrison. 1966. Seasonal variations of available carbohydrates in bitterbrush. J. Wildl. Manage. 30(1):168-172.

McCreight, Richard W. 1981. Microwave ovens for drying live wildland fuels: An assessment. USDA, For. Serv. Res. Note PSW-349. Pacif. Southw. For. and Range Exp. Sta., Berkeley, CA. 5 p.

McCulloch, C. Y., D. C. Wallmo, and P. F. Ffolliott. 1965. Acorn yield of Gambel oak in northern Arizona. USDA, For. Serv. Res. Note RM-48. Rocky Mt. For. and Range Exp. Sta., Ft. Collins, CO. 2 p.

McGee, John M. 1982. Small mammal populations in an unburned and early fire successional sagebrush community. J. Range Manage. 35:177-179.

McMahon, C. K., C. W. Adkins, and S. L. Rodgers. 1987. A video image analysis system for measuring fire behavior. Fire Manage. Notes 47(1):10-15.

McMurray, Nancy E. 1988. *Pinus ponderosa var. scopulorum*. IN William C. Fischer. Fire Effects Information System. [Data base]. Missoula, Montana. USDA, For. Serv. Intermt. Res. Sta. Intermt. Fire Sciences Lab. Magnetic tape reels; 9 track; 1600 bpi; ASCII with Common LISP present.

McPherson, J. K. and C. H. Muller. 1969. Allelopathic effect of *Adenostoma fasciculatum*, "chamise," in the California chaparral. Ecol. Monogr. 39:177-198.

McRae, Douglas J., Martin E. Alexander, and Brian J. Stocks. 1979. Measurement and description of fuels and fire behavior on prescribed burns: a handbook. Canad. Forest. Serv., Dept. Environ. Rep. O-X-287. Great Lakes For. Res. Centre, Sault Ste. Marie, ON. 58 p.

Meyer, Bernard S., Donald B. Anderson, Richard H. Bohning, and Douglas G. Fratianne. 1973. Introduction to plant physiology. D. Van Nostrand Company. New York. 565 p.

Michels, Joseph. 1973. Dating methods in archaeology. Seminar Press, New York. p. 193.

Miller, Melanie. 1976. Shrub sprouting response to fire in a Douglas-fir/western larch ecosystem. M.S. thesis. Univ. Mont., Missoula. 124 p.

Miller, Melanie. 1977. Response of blue huckleberry to prescribed fires in a western Montana larch-fir forest. USDA, For. Serv. Res. Pap. INT-188. Intermt. For. and Range Exp. Sta., Ogden, UT. 33 p.

Miller, Melanie. 1978. Effect of growing season on sprouting of blue huckleberry. USDA, For. Serv. Res. Note INT-240. Intermt. For. and Range Exp. Sta., Ogden, UT. 8 p.

Miller, Melanie. 1981. Personal observation. Fire ecologist. USDI, Bur. Land Manage., Fairbanks District Ofice, Fairbanks, AK.

Miller, Melanie. 1988. Personal observation. Fire ecologist. USDI, Bur. Land Manage., Boise Interag. Fire Center, Boise, ID.

Moen, Aaron N. 1979. Animal behavior, p. 107-116. IN Richard D. Teague and Eugene Decker (eds.). Wildlife conservation: Principles and practices. The Wildlife Society, Washington, D.C.

Moore, Robert. 1989. Personal conversation with Loren Anderson.

Morgan, Penelope and Leon F. Neuenschwander. 1988. Shrub response to high and low severity burns following clear-cutting in northern Idaho. West. J. Appl. For. 3(1):5-9.

Mueggler, Walter F. 1976. Ecological role of fire in western woodland and range ecosystems, p. 1-9. IN Frank E. Busby and Edward Storey (eds.). Use of prescribed burning in western woodland and range ecosystems: A symposium. Utah Agric. Exp. Sta., Utah State Univ., Logan.

Mueggler, Walter F. 1983. Variation in production and seasonal development of mountain grasslands in western Montana. USDA, For. Serv. Res. Pap. INT-316. Intermt. For. and Range Exp. Sta., Ogden, UT. 16 p.

Mueller-Dombois, D. and H. Ellenberg. 1974. Aims and methods of plant ecology. John Wiley and Sons, New York. 547 p.

Muller, C. H., R. B. Hanawalt, and J. K. McPherson. 1968. Allelopathic control of herb growth in the fire cycle of California chaparral. Bull. Torrey Bot. Club 95:225-231.

Mutch, R. W. and O. W. Gastineau. 1970. Timelag and equilibrium moisture content of reindeer lichen. USDA, For. Serv. Res. Pap. INT-76. Intermt. For. and Range Exp. Sta., Ogden, UT. 8 p.

Neitro, William A., Virgil W. Binkley, Steven P. Cline, R. William Mannan, Bruce G. Marcot, Douglas Taylor, and Frank F. Wagner. 1985. Snags (wildlife trees), p. 129-169. IN E. Reade Brown (ed.). Management of wildlife and fish habitats in forests of western Oregon and Washington. Part 1 - Chapter narratives. USDA, For. Serv. Publ. No. R6-F&WL-192-1985. Pacif. Northw. Reg., Portland, Oregon.

Nelson, J. G. 1973. The last refuge. Harvest House, Montreal, Quebec, Canada. 230 p.

Nissley, S. D., R. J. Zasoski, and R. E. Martin. 1980. Nutrient changes after prescribed surface burning of Oregon ponderosa pine stands, p. 214-219. IN R. E. Martin and six others (eds.). Proc. sixth conf. on fire and forest meterol. Soc. Amer. Forest., Washington, D.C.

Norum, Rodney A. 1975. Characteristics and effects of understory fires in western larch/Douglas-fir stands. Ph.D. Dissertation. Univ. of Montana, Missoula. 155 p.

Norum, Rodney A. 1977. Preliminary guidelines for prescribed burning under standing timber in western larch/Douglas-fir forests. USDA, For. Serv. Res. Note INT-229. Intermt. For. and Range Exp. Sta., Ogden, UT. 15 p.

Norum, Rodney A. 1987. Ignition and firing: How they meet and/or interact with other prescription variables. Lesson Plan. IN Fire Prescription Writing. Boise Interag. Fire Center, Boise, ID.

Norum, Rodney A. 1992. Personal conversation with Melanie Miller.

Norum, Rodney A. and William C. Fischer. 1980. Determining the moisture content of some dead forest fuels using a microwave oven. USDA, For. Serv. Res. Note INT-177. Intermt. For. and Range Exp. Sta., Ogden, UT. 7 p.

Norum, Rodney A. and Melanie Miller. 1981. Unpublished data on file at USDI, Bur. Land Manage., Div. Fire and Aviat. Pol. and Manage., Boise, ID.

Norum, Rodney A. and Melanie Miller. 1984. Measuring fuel moisture content in Alaska: Standard methods and procedures. USDA, For. Serv. Gen. Tech. Rep. PNW-171. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 34 p.

Noste, Nonan V. and Charles L. Bushey. 1987. Fire response of shrubs of dry forest habitat types in Montana and Idaho. USDA, For. Serv. Gen. Tech. Rep. INT-239. Intermt. Res. Sta., Ogden, UT. 22 p.

Noxon, J. S. and D. A. Marcus. 1983. Wildfire-induced cliff face exfoliation and potential effects on cultural resources in the Needles District of Canyonlands National Park, Utah. Southwestern Lore 49(2):1-8.

Odum, Eugene P. 1966. Fundamentals of ecology. 2nd ed. W. B. Saunders Co., Philadelphia, PA. 546 p.

Ottmar, Roger E., Mary F. Burns, Janet N. Hall, and Aaron D. Hanson. 1993. CONSUME Users Guide. USDA, For. Serv. Gen. Tech. Rep. PNW-GTR-304. Pacif. Northw. Res. Sta., Portland, OR. 118 p.

Ottmar, Roger D., Colin C. Hardy, and Robert E. Vihnanek. 1990. Stereo photo series for quantifying forest residues in the Douglas-fir-hemlock type of the Willamette National Forest. USDA, For. Serv. Gen. Tech. Rep. PNW-GTR-258. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 63 p.

Ottmar, Roger D. and David V. Sandberg. 1985. Calculating moisture content of 1000-hour timelag fuels in western Washington and western Oregon. USDA, For. Serv. Res. Pap. PNW-336. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 16 p.

Owensby, Clenton E. and John Bruce Wyrill, III. 1973. Effects of range burning on Kansas Flint Hills soil. J. Range Manage. 26:185-188.

Parker, G. R., J. W. Maxwell, L. D. Morton, and G. E. J. Smith. 1983. Ecology of the lynx *(Lynx canadensis)* on Cape Breton Island. Can. J. Zool. 61:770-786.

Parker, V. Thomas. 1984. Correlation of physiological divergence with reproductive mode in chaparral shrubs. Madrono 31(4):231-242.

Parker, V. Thomas. 1987. Can native flora survive prescribed burns? Fremontia 15(2):3-6.

Parker, V. Thomas. 1989. Maximizing vegetation response on management burns by identifying fire regimes, p. 87-91. IN Neil H. Berg (tech. coord.). Proc. symp. on fire and watershed management. USDA, For. Serv. Gen. Tech. Rep. PSW-109. Pacif. Southw. For. and Range Exp. Sta., Berkeley, CA.

Pase, Charles P. and Carl E. Granfelt. 1977. The use of fire on Arizona rangelands. Arizona Interag. Range Comm. Pub. No. 4. 15 p.

Paysen, Timothy E. and Jack D. Cohen. 1990. Chamise chaparral dead fuel fraction is not reliably predicted by age. W. J. Appl. Forest. 5(4):127-131.

Pechanec, J. F., G. Stewart, and J. P. Blaisdell. 1954. Sagebrush burning - Good and bad. USDA Farmer's Bull. 1948. 34 p.

Peech, Michael. 1965. Hydrogen-ion activity, p. 914-932. IN C. A.

Black (ed.). Methods of soil analysis. Part 2: Chemical and microbiological properties. Amer. Soc. Agron., Madison, WI.

Peek, James M., Dennis A. Demarchi, and Donald E. Stucker. 1984. Bighorn sheep and fires: Seven case histories, p. 36-43. IN James E. Lotan and James K. Brown (eds.). Proc. - Fire's effects on wildlife habitat. USDA, For. Serv. Gen. Tech. Rep. INT-186. Intermt. For. and Range Exp. Sta., Ogden, UT.

Peek, J. M., R. A. Riggs, and J. L. Lauer. 1979. Evaluation of fall burning on bighorn sheep winter range. J. Range Manage. 32:430-432.

Pellant, Mike. 1989. Evaluation. Lesson Plan. IN Fire Effects on Public Lands. Boise Interag. Fire Center. Boise, Idaho.

Pennak, Robert W. 1964. Collegiate dictionary of zoology. Ronald Press Co., New York. 583 p.

Perry, D. A., R. Molina, and M. P. Amaranthus. 1987. Mycorrhizae, mycorrhizospheres, and reforestation; current knowledge and research needs. Can. J. For. Res. 17:929-940.

Petersburg, Stephen. 1989. Personal conversation with Melanie Miller.

Peterson, David L. 1985. Crown scorch volume and scorch height: Estimates of postfire tree condition. Can. J. For. Res. 15:596-598.

Peterson, Terry D. 1989. Characteristics of *Ceanothus*. IN Forest vegetation management workshop. Oreg. State Univ., Corvallis. Unpaged.

Philpot, Charles W. and Robert W. Mutch. 1971. The seasonal trends in moisture content, ether extractives, and energy of ponderosa pine and Douglas-fir needles. USDA, For. Serv. Res. Pap. INT-102. Intermt. For. and Range Exp. Sta., Ogden, UT. 21 p.

Pidanick, Bill. 1982. Prescribed fire/cultural artifacts: Investigating the effects. Pacif. Southw. Log. USDA, For. Serv., Pacif. Southw. Reg., San Francisco, CA. 2 p.

Pieper, R. D. 1973. Measurement techniques for herbaceous and shrubby vegetation. Dept. Anim., Range, and Wildl. Sci., New Mex. State Univ., Las Cruces, NM. 187 p.

Pilles, Peter J. 1982. Prescribed fire management and cultural resource management. Manuscript. USDA, For. Serv. Southw. Reg., Coconino Nat. For., Flagstaff, AZ. 11 p.

Platts, W. S., W. F. Megahan, and G. W. Minshall. 1983. Methods for evaluating stream, riparian, and biotic conditions. USDA, For. Serv. Gen. Tech. Rep. INT-138. Intermt. For. and Range Exp. Sta., Ogden, UT. 70 p.

Pritchett, William L. 1979. Properties and management of forest soils. John Wiley & Sons, New York. 500 p.

Purdy Barbara A. and H. K. Brooks. 1971. Thermal alteration of silica minerals: An archaeological approach. Science 173: 322-325.

Quinn, R. D. 1979. Effects of fire on small mammals in the chaparral. Calif. Nev. Wildl. Trans. 1979:125-133.

Raabe, O. G. 1984. Site selective sampling criteria for the thoracic and respirable mass fractions. Ann. Am. Conf. Ind. Hyg. 11:53-65.

Racine, Charles H. and Marilyn M. Racine. 1979. Tundra fires and two archaeological sites in the Seward Peninsula, Alaska. Arctic 32(1): 76-79.

Raison, R. J. 1979. Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: A review. Plant and Soil 51:73-108.

Range Term Glossary Committee. 1974. A glossary of terms used in range management. Soc. Range Manage., Denver. CO. 36 p.

Ranger, G. E. and F. F. Frank. 1978. The 3-F erosion bridge - A new tool for measuring soil erosion. Calif. Dept. Forest. and Fire Prot. Pub. 23. Sacramento, CA.

Rasmussen, G. Allen and Henry A. Wright. 1988. Germination requirements of flameleaf sumac. J. Range Manage. 41(1):48-52.

Reaves, Jimmy L., Charles G. Shaw, III, and John E. Mayfield. 1990. The effects of *Trichoderma* spp. isolated from burned and non-burned forest soils on the growth and development of *Armillaria ostoyae*. Northw. Sci. 64(1):39-44.

Reese, Kerry P. and John T. Ratti. 1988. Edge effect: A concept under scrutiny. Trans. N. Amer. Wildl. Conf. 53:127-136.

Reifsnyder, William E. 1961. Seasonal variation in the moisture content of green leaves of mountain laurel. For. Sci. 7(1): 16-23.

Reinhardt, Elizabeth, James K. Brown, William C. Fischer, and Russell T. Graham. 1991. Woody fuel and duff consumption by prescribed fire in northern Idaho mixed conifer logging slash. USDA, For. Serv. Res. Pap. INT-443. Intermt. Res. Sta., Ogden, UT. 22 p.

Reinhardt, Elizabeth D. and Kevin C. Ryan. 1988a. Eight-year tree growth following prescribed underburning in a western Montana Douglas-fir/western larch stand. USDA, For. Serv. Res. Note INT-387. Intermt. Res. Sta., Ogden, UT. 6 p.

Reinhardt, Elizabeth D. and Kevin C. Ryan. 1988b. Estimating tree mortality resulting from prescribed fire. Fire Manage. Notes 49(4): 30-36.

Reinhardt, T. E. 1989. Firefighter smoke exposure at prescribed burns. A study and action recommendation. Unpubl. Rep. USDA, For. Serv. Pacif. Northw. For. and Range Exp. Sta., Seattle, WA. 86 p. plus appen.

Renard, K. G., G. R. Foster, G. A. Weesies, and J. P. Porter. 1991. RUSLE: Revised universal soil loss equation. J. Soil and Water Conserv. 46(1):30-33.

Richards, J. H. and M. M. Caldwell. 1985. Soluble carbohydrates, concurrent photosynthesis and efficiency in regrowth following defoliation: A field study with *Agropyron* species. J. Appl. Ecol. 22:907-920.

Richards, Leon W. 1940. Effect of certain chemical attributes of vegetation on forest inflammability. J. Agric. Res. 60(12): 833-838.

Richter, D. D. and C. W. Ralston. 1982. Prescribed fire: Effects on water quality and forest nutrient cycling. Science 215(4533):661-663.

Riedel, A. L. and S. J. Petersburg. 1989. Live fuel moisture in Wyoming big sagebrush *(Artemisia tridentata wyomingensis)* in Dinosaur National Monument. Manuscript on file at Dinosaur Natl. Mon., Dinosaur, CO. 19 p.

Rietveld, W. J. 1976. Cone maturation in ponderosa pine foliage scorched by wildfire. USDA, For. Ser. Res. Note RM-317. Rocky Mt. For. and Range Exp. Sta., Ft. Collins, CO. 7 p.

Robb, L. A. 1987. Gastropod intermediate host of lungworm *(Nematoda: Protostrongylidae)* on a bighorn sheep winter range: Aspects of transmission. M.S. thesis, Univ. of Alberta, Edmonton. 111 p.

Rodriguez-Barrueco, C. and G. Bond. 1968. Nodule endophytes in the genus *Alnus*, p. 185-192. IN J. M. Trappe, J. F. Franklin, R. F. Tarrant, and G. M. Hanson (eds.). Biology of alder. Pacif. Northw. For. and Range Exp. Sta., Portland, OR.

Rogers, G. F. and M. K. Vint. 1987. Winter precipitation and fire in the Sonoran desert. J. Arid Environ. 13:47-52.

Rosenberg, K. V. and M. G. Raphael. 1986. Effects of forest fragmentation in Douglas-fir forests, p. 263-272. IN J. Verner, M. L. Morrison, and C. J. Ralphs (eds.). Wildlife 2000: Modeling habitat relationships of terrestrial vertebrates. Univ. Wisc. Press., Madison.

Rosentreter, Roger. 1989. Personal conversation with Loren Anderson.

Rotenberry, John T. and John A. Wiens. 1978. Nongame bird communities in northwestern rangelands, p. 32-46. IN R. M. DeGraaf (tech. coord.). Proc. nongame bird habitat management in the coniferous forests of the western U.S. USDA, For. Serv. Gen. Tech. Rep. PNW-64. Pacif. Northw. For. and Range Exp. Sta., Portland, OR.

Rothermel, Richard C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA, For. Serv. Res. Pap. INT-114. Intermt.

For. and Range Exp. Sta., Ogden, UT. 40 p.

Rothermel, Richard C. 1980. Personal letter to Rodney A. Norum. September 16, 1980.

Rothermel, Richard C. 1983. How to predict the spread and intensity of forest and range fires. USDA, For. Serv. Gen. Tech. Rep. INT-143. Intermt. For. and Range Exp. Sta., Ogden, UT.

161 p.

Rothermel, Richard C. 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. USDA, For. Serv. Res. Pap. INT-438. Intermt. Res. Sta., Ogden, UT. 46 p.

Rothermel, Richard C. and J. E. Deeming. 1980. Measuring and interpreting fire behavior for correlation with fire effects. USDA, For. Serv. Gen. Tech. Rep. INT-93. Intermt. For. and Range Exp. Sta., Ogden, UT. 4 p.

Rothermel, Richard C., Ralph A. Wilson, Jr., Glen A. Morris, Stephen S. Sackett. 1986. Modeling moisture content of fine dead wildland fuels: Input to the BEHAVE Fire Prediction System. USDA, For. Serv. Gen. Tech. Rep. INT-359. Intermt. Res. Sta., Ogden, UT. 4 p.

Roundy, Bruce A., James A. Young, Greg J. Cluff, and Raymond A. Evans. 1983. Measurement of soil water on rangelands. USDA, Agric. Res. Serv. Res. Results West. Ser. No. 31. Oakland, CA. 27 p.

Rowe, J. S. 1983. Concepts of fire effects on plant individuals and species, p. 135-151. IN R. W. Wein and D. A. Maclean (eds.). The role of fire in northern circumpolar ecosystems. SCOPE Rep., No. 18. John Wiley and Sons. New York. 322 p.

Ryan, Kevin C. 1982. Evaluating potential tree mortality from prescribed burning, p. 167-178. IN David M. Baumgartner (comp.). Symp. - Site preparation and fuels management in steep terrain. Wash. State Univ. Coop. Extension, Pullman.

Ryan, Kevin C. 1983. Techniques for assessing fire damage to trees, p. 1-11. IN James E. Lotan (ed.) Proc. Symp. on Fire - Its field effects.

Intermountain Fire Council. Missoula, MT.

Ryan, Kevin C. 1987. Techniques for writing fire prescriptions to minimize or enhance tree mortality. Lesson Plan. IN Fire Prescription Writing. Boise Interagency Fire Center, Boise, ID.

Ryan, Kevin C. and Nonan V. Noste. 1985. Evaluating prescribed fires, p. 230-238. IN Proc. - Symp. and workshop on wilderness fire. USDA, For. Serv. Gen. Tech. Rep. INT-182. Intermt. For. and Range Exp. Sta., Ogden, UT.

Ryan, Kevin C., David L. Peterson, and Elizabeth D. Reinhardt. 1988. Modeling long-term fire-caused mortality of Douglas-fir. For. Sci. 34(1):190-199.

Sackett, Steve. 1981. Designing fuel moisture sampling systems. Lesson plan. IN Fire Management for Managers. Natl. Adv. Resour. Tech. Center. Marana, AZ.

Samuel, M. J. and E. J. DePuit. 1987. Competition and plant establishment, p. 138-148. IN Gary W. Frasier and Raymond A. Evans (eds.). Proc. symp. seed and seedbed ecology of rangeland plants. Tucson, AZ.

Sandberg, David. 1980. Duff reduction by prescribed underburning in Douglas-fir. USDA, For.Serv. Res. Pap. PNW-272. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 18 p.

Sandberg, D. V. 1987. Progress in reducing emissions from prescribed forest burning in western Washington and western Oregon, 13 p. IN Proc. 23rd ann. meeting Air Pollution Control Assoc. Pacif. Northw. Internatl. Sect., Pittsburgh, PA.

Sandberg, David V. and Frank N. Dost. 1990. Effects of prescribed fire on air quality and human health, p. 191-218. IN John D. Walstad, Steven R. Radosevich, and David V. Sandberg (eds.). Natural and prescribed fire in Pacific Northwest forests. Oreg. State Univ. Press, Corvallis.

Sandberg, D. V. and J. Peterson. 1987. Daily slash burn emissions inventory design, part II. U.S. Environ. Prot. Agency. Fin. Rep. EPA

Contr. IAG EPA 83-291. Office Air Prog. - Reg. X, Seattle, WA.

Sandberg, D. V., J. M. Pierovich, D. G. Fox, and E. W. Ross. 1978. Effects of fire on air: A state-of- knowledge review. USDA, For. Serv. Gen. Tech. Rep. WO-9. Washington, D.C.

Sandberg, David V. and Franklin R. Ward. 1981. Predictions of fire behavior and resistance to control for use with photo series for the Douglas-fir - hemlock type and the coastal Douglas-fir - hardwood type. USDA, For. Serv. Gen. Tech. Rep. PNW-116. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 60 p.

SAS Institute. 1985. SAS user's guide: Statistics. SAS Institute, Inc., Cary, NC. 584 p.

Sauer, Ronald H. and Daniel W. Uresk. 1976. Phenology of steppe plants in wet and dry years. Northw. Sci. 50(3):133-138.

Savory, Alan. 1988. Holistic resource management. Island Press, Washington, D.C. 564 p.

Schier, G. A. 1972. Apical dominance in multishoot culture from aspen roots. For. Sci. 18:147- 149.

Schier, George A. 1975. Deterioration of aspen clones in the middle Rocky Mountains. USDA, For. Serv. Res. Pap. INT-170. Intermt. For. and Range Exp. Sta., Ogden, UT. 14 p.

Schier, George A. 1983. Vegetative regeneration of gambel oak and chokecherry from excised rhizomes. For. Sci. 29(3):499-502.

Schier, George A., John R. Jones, and Robert P. Winokur. 1985. Vegetative regeneration, p. 29-33. IN Norbert V. DeByle and Robert P. Winokur (eds.). Aspen: Ecology and management in the western United States. USDA, For. Serv. Gen. Tech. Rep. RM-119. Rocky Mt. For. and Range Exp. Sta., Ft. Collins, CO.

Schiff, Ashley L. 1962. Fire and water: Scientific heresy in the Forest Service. Harvard Univ. Press, Cambridge, MA. 225 p.

Schmidt, Marcus. 1992. Great Basin live fuel moisture project. Biweekly report. October 13, 1992. USDI, Bur. Land Manage., Nevada State Office, Div. Fire and Aviat. Manage., Reno. Unpaged.

Schmidt, Wyman C. and James E. Lotan. 1980. Phenology of common forest flora of the northern Rockies - 1928 to 1937. USDA, For. Serv. Res. Pap. INT-259. Intermt. For. and Range Exp. Sta., Ogden, UT. 20 p.

Schroeder, Mark J. and Charles C. Buck. 1970. Fire weather . . . A guide for application of meteorological information to forest fire control operations. USDA, For. Serv. Agric. Handb. 360. 229 p.

Scott, Douglas. 1987. Personal conversation with Dr. Richard Hanes.

Seabloom, Robert W., Rodney D. Sayler, and Stanley A. Ahler. 1991. Effects of prairie fires on archaeological artifacts. Park Science 11(1): 1-3.

Sestak, M. L. and A. R. Riebau. 1988. SASEM: Simple approach smoke estimation model. USDI, Bur. Land Manage. Tech. Note 382. BLM/YA/PT-88/003 + 7300. Serv. Center, Denver, CO. 31 p.

Sestak, M. L., A. R. Riebau, and M. Matthews. 1991. A tiered approach to smoke management on government lands, p. 470-477. IN Patricia L. Andrews and Donald F. Potts (eds.). Proc. 11th Conf. on Fire and For. Meteor. Soc. of Amer. For.

Settergren, Carl D. 1969. Reanalysis of past research on effects of fire on wildland hydrology. Coll. Agric. Exp. Sta. Res. Bull. 954. Univ. Missouri, Columbia. 16 p.

Shafizadeh, Fred, Peter P. S. Chin, and William F. DeGroot. 1977. Effective heat content of green forest fuels. For. Sci. 23(1):81-87.

Sharrow, S. H. and H. A. Wright. 1977. Proper burning intervals for tobosagrass in west Texas based on nitrogen dynamics. J. Range Manage. 30:343-346.

Shearer, Raymond C. 1975. Seedbed characteristics in western larch forests after prescribed burning. USDA, For. Serv. Res Pap. INT-167. Intermt. For. and Range Exp. Sta., Ogden, UT.

26 p.

Short, H. L. 1982. Techniques for structuring wildlife guilds to evaluate impacts on wildlife communities. USDI, Fish and Wildl. Serv. Spec. Rep. 244.

Short, H. L. 1983. Wildlife guilds in Arizona desert habitats. USDI, Bur. Land Manage. Tech. Note 362. Serv. Center, Denver, CO. 258 p.

Simard, Albert J. 1968. The moisture content of forest fuels - I. A review of the basic concepts. For. Fire Res. Inst. Info. Rep. FF-X-14. Canada Dept. of Forest. and Rural Developm., Ottawa, ON. 47 p.

Simard, Albert J., James E. Eenigenburg, and Richard W. Blank. 1984. Predicting fuel moisture in jack pine slash: A test of two systems. Can. J. For. Res. 14: 68-76.

Simard, A. J. and W. A. Main. 1982. Comparing methods of predicting jack pine slash moisture. Can. J. For. Res. 12: 793-802.

Smith, Graham W., Nicholas C. Nydegger, and Dana L. Yensen. 1984. Passerine bird densities in shrubsteppe vegetation. J. Field Bio. 55:261-264.

Smith, M. A. 1981. Prescribed burning: Effective control of sagebrush in Wyoming. Wyo. Agric. Exp. Sta. Bull. No. RJ-165. Univ. of Wyo., Laramie. 12 p.

Smith, M. A., J. L. Dodd, and J. D. Rogers. 1985. Prescribed burning on Wyoming rangeland. Agric. Ext. Serv. Bull. B-810, Univ. of Wyo., Laramie. 25 p.

Smith, Michael A., Henry A. Wright, and Joseph L. Schuster. 1975. Reproductive characteristics of redberry juniper. J. Range Manage. 28(2):126-128.

Smith, S. D., S. C. Bunting, and M. Hironaka. 1986. Sensitivity of frequency plots for detecting vegetation change. Northw. Sci. 60:279-286.

Soil Survey Staff. 1975. Soil taxonomy. USDA Handbk. 436. Sup. Doc., U.S. Govt. Print. Off., Washington, D.C. 754 p.

Sprent, Janet I. 1987. The ecology of the nitrogen cycle. Cambridge Univ. Press, Cambridge, GB. 151 p.

Stanton, Frank W. 1975. Determining recovery potential of burned plants following range fire. Rangeman's Journal 2(5): 152.

Starkey, Edward, E. 1985. Impact of fire on nongame wildlife, p. 48-51. IN Ken Sanders and Jack Durham (eds.). Rangeland fire effects: A symposium. USDI, Bur. Land Manage., Idaho

State Office, Boise.

StatSoft, Inc. 1987. CSS (Complete Statistical System). StatSoft, Inc., Tulsa, OK. 2 Vols., 1130 and 840 p.

Stein, William I. 1986. Regeneration outlook on BLM lands in the Siskiyou Mountains. USDA, For. Serv. Res. Pap. PNW-349. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 104 p.

Stickney, Peter F. 1986. First decade plant succession following the Sundance forest fire, northern Idaho. USDA, For. Serv. Gen. Tech. Rep. INT-197. Intermt. Res. Sta., Ogden, UT.

26 p.

Stone, E. C. and G. Juhren. 1953. The effects of fire on the germination of the seed of *Rhus ovata* Wats. Amer. J. Bot. 38:368-372.

Striffler, W. D. and E. W. Mogren. 1971. Erosion, soil properties, and revegetation following a severe burn in the Colorado Rockies, p. 25-36. IN C. W. Slaughter, Richard J. Barney, and G. M. Hanson (eds.). Fire in the northern environment - A symposium. USDA, For. Serv. Pacif. Northw. For. and Range Exp. Sta., Portland, OR.

Sturges, David L. 1983. Long-term effects of big sagebrush control on vegetation and soil water. J. Range Manage. 36:760-765.

Sweeney, J. R. 1956. Responses of vegetation to fire. Univ. Calif. Publ.

Bot. 28:143-231.

Switzer, Ronald R. 1974. The effects of forest fire on archaeological sites in Mesa Verde National Park, Colorado. The Artifact 12(3):1-8.

Szaro, Robert C. 1986. Guild management: An evaluation of avian guilds as a prediction tool. Environ. Manage. 10:681-688.

Tande, Gerald F. 1980. Interpreting fire history in Jasper National Park, Alberta, p. 31-34. IN Marvin A. Stokes and John H. Dieterich (tech. coord.). Proc. fire history workshop. USDA, For. Serv. Gen. Tech. Rep. RM-81. Rocky Mt. For. and Range Exp. Sta., Ft. Collins, CO.

Tappeiner, John C., Timothy B. Harrington, and John D. Walstad. 1984. Predicting recovery of tanoak *(Lithocarpus densiflorus)* and pacific madrone *(Arbutus menziesii)* after cutting or burning. Weed Sci. 32:413-417.

Thill, Donald C., K. George Beck, and Robert H. Callihan. 1984. The biology of *Bromus tectorum*. Weed Sci. 32, Suppl. 1:7-12.

Thomas, Jack Ward (ed.). 1979. Wildlife habitats in managed forests: The Blue Mountains of Oregon and Washington. USDA, For. Serv. Agric. Handbk. No. 553. Sup. Doc. G.P.O. Washington, D.C. 512 p.

Thomas, Jack Ward, Chris Maser, and Jon E. Rodiek. 1979. Edges. 17 p. IN Wildlife habitats in managed rangelands - The Great Basin of southeastern Oregon. USDA, For. Serv. Gen. Tech. Rep. PNW-85. Pacif. Northw. For. and Range Exp. Sta., Portland, OR.

Thurston, Robert V., Rosemarie C. Russo, Carlos M. Fetterolf, Jr., Thomas A. Edsall, and Yates M. Barber, Jr. 1979. A review of the EPA Red Book: Quality criteria for water. Amer. Fisheries Soc., Bethesda, MD. 313 p.

Tiedemann, Arthur R. 1987. Combustion losses of sulfur from forest foliage and litter. For. Sci. 33:216-223.

Tiedemann, A. R., W. P. Clary, and R. J. Barbour. 1987. Underground systems of gambel oak *(Quercus gambelii)* in central Utah. Amer. J. Bot. 74(7):1065-1071.

Tiedemann, Arthur R., Carol E. Conrad, John H. Dieterich, James W. Hornbeck, Walter F. Megahan, Leslie A. Viereck, and Dale D. Wade. 1979. Effects of fire on water: A state-of-knowledge review. USDA, For. Serv. Gen. Tech. Rep. WO-10. Washington, D.C. 28 p.

Tisdale, Samuel L. and Werner L. Nelson. 1975. Soil fertility and fertilizers, 3rd ed. Macmillan and Sons., Inc. New York. 694 p.

Tomback, Diana F. 1986. Post-fire regeneration of Krummholz whitebark pine: A consequence of nutcracker seed caching. Madrono 33(2):100-110.

Trappe, James M. 1981. Mycorrhizae and productivity of arid and semiarid rangelands, p. 581-599. IN Advances in food producing systems for arid and semi-arid lands. Academic Press, Inc., New York.

Traylor, Diane. 1981. Effects of La Mesa Fire on Bandelier's cultural resources, p. 97-102. IN La Mesa fire symp. USDOE, Los Alamos Nat. Lab., Los Alamos, NM.

Trevett, M. F. 1956. Observation on the decline and rehabilitation of lowbush blueberry fields. Maine Agric. Exp. Sta. Misc. Publ. 626. Univ. Maine, Orono. 21 p.

Trlica, M. J. 1977. Distribution and utilization of carbohydrate reserves in range plants, p. 73-96. IN Ronald E. Sosebee, and 9 others. Rangeland plant physiology. Soc. for Range Manage. Denver, CO.

Turner, Frederick B. and David C. Randall. 1987. The phenology of desert shrubs in southern Nevada. J. Arid Environ. 13:119-128.

Urness, Phillip J. 1985. Managing lodgepole pine ecosystems for game and range values, p. 297-304. IN David W. Baumgartner, Richard G. Krebill, James T. Arnott, and Gordon F. Weetman (comp. and ed.). Symp. proc.: Lodgepole pine, the species and its management. Coop. Exten. Serv., Wash. State Univ., Pullman.

USDA-Forest Service, and Johns Hopkins University. 1989. The effects of forest fire smoke on firefighters: A comprehensive study plan. Third draft. Prepared for: Congressional Committee on Appropriations for Title II-Related Agencies and the National Wildfire Coordinating Group. Intermt. Res. Sta., Fire Chem. Res. Work Unit, Missoula, MT, and School of Hygiene and Public Health, Johns Hopkins Univ., Baltimore, MD. 84 p. plus appen.

USDD-Corps of Engineers. 1989. Effects of forest fires and burn programs on archaeological resources. Corps of Engin., Waterways Exp. Sta., Archaeological Sites Protection and Preserv. Notebook, Tech. Note I-8. Vicksburg, MS.

USDI-Bureau of Land Management, 1985a. Rangeland monitoring - Trend studies. Tech. Ref. 4400-4. Bur. Land Manage., Serv. Center, Denver, CO. 130 p.

USDI-Bureau of Land Management. 1985b. Emergency fire rehabilitation, Bureau Manual Handbook H-1742-1. Bur. Land Manage., Washington, D.C. 17 p.

USDI-Fish and Wildlife Service. 1989. Protection proposed for the northern spotted owl. Endangered Species Tech. Bull. Vol. XIV No. 7. 12 p.

USDI-National Park Service. 1992. Fire monitoring handbook. Natl. Park Serv., Western Region. San Francisco, CA. 134 p. plus appendices.

Van Wagner, C. E. 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. 7:23- 34.

Van Wagner, C. E. 1979. A laboratory study of weather effects on drying rate of jack pine litter. Can. J. For. Res. 9: 267-275.

Viereck, L. A. and M. J. Foote. 1979. Permafrost, p. 17-21. IN L. A. Viereck, and C. T. Dyrness (eds.). Ecological effects of the Wickersham Dome fire near Fairbanks, Alaska. USDA, For. Serv. Gen. Tech. Rep. PNW-90. Pacif. Northw. For. and Range Exp. Sta., Portland, OR.

Viereck, Leslie A. and Linda A. Schandelmeier. 1980. Effects of fire in Alaska and adjacent Canada - A literature review. USDI, Bur. Land Manage. Tech. Rep. 6. Alaska State Office, Anchorage. 124 p.

Viney, Neil R. 1991. A review of fine fuel moisture modelling. Intl. J. Wildl. Fire 1(4): 215-234.

Vogl, Richard J. 1978. A primer of ecological principles - Book one. Pyro Unlimited Pub., Cypress, Calif. 172 p.

Volland, Leonard A. and John D. Dell. 1981. Fire effects on Pacific Northwest forest and range vegetation. USDA, For. Serv. Pacif. Northw. Reg., Range Manage. and Aviat. and Fire Manage., Portland, OR. 23 p.

Wade, Dale D. 1986. Linking fire behavior to its effects on living plant tissue. IN Proc. Ann. Conv. Soc. Amer. Foresters. Birmingham, AL. Unpaged.

Wade, Dale D. and R.W. Johansen. 1986. Effects of fire on southern pine: Observations and recommendations. USDA, For. Serv. Gen. Tech. Rep. SE-41. Southea. For. Exp. Sta., Asheville, NC. 14 p.

Wagle, R. F. 1981. Fire: Its effects on plant succession and wildlife in the southwest. Univ. of Ariz., Tucson. 82 p.

Wagle, R. F. and J. H. Kitchen, Jr. 1972. Influence of fire on soil nutrients in a ponderosa pine type. Ecology 53:118-125.

Ward, Franklin R. and David V. Sandberg. 1981a. Predictions of fire behavior and resistance to control for use with photo series for the Sierra mixed conifer type and the Sierra true fir type. USDA, For. Serv. Gen. Tech. Rep. PNW-114. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 48 p.

Ward, Franklin R. and David V. Sandberg. 1981b. Predictions of fire behavior and resistance to control for use with photo series for the ponderosa pine type, ponderosa pine and associated species type, and lodgepole pine type. USDA, For. Serv. Gen. Tech. Rep. PNW-115. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 46 p.

Ward, Peter. 1968. Fire in relation to waterfowl habitat of the Delta marshes, p. 255-268. IN Proc. Tall Timbers Fire Ecol. Conf. No. 8. Tall Timbers Res. Sta., Tallahassee, FL.

Watt, Kenneth E. F. 1972. Man's efficient rush toward deadly dullness,

p. 358-366. IN Alan Ternes (ed.). Ants, Indians and little dinosaurs. Am. Museum of Natur. Hist., Washington, D.C.

Wecker, Stanley C. 1964. Habitat selection. Sci. Amer. 211:109-116.

Welch, Pat and Tirzo Gonzalez. 1982. Research design: Prescribed burn impact evaluation upon cultural resources, LMDA and Thing Mountain chaparral management projects. Manuscript. USDI, Bur. Land Manage., El Centro, CA. 8 p.**Wells, Carol G., Ralph E. Campbell, Leonard F. DeBano, Clifford E. Lewis, Richard L. Frederiksen, E. Carlyle Franklin, Ronald C. Froelich, and Paul H. Dunn. 1979.** Effects of fire on soil: A state-of-knowledge review. USDA, For. Serv. Gen. Tech. Rep. WO-7. Washington, D.C. 34 p.

Wendel, George W. and Theodore G. Storey. 1962. Seasonal moisture fluctuations in four species of pocosin vegetation. USDA, For. Serv. Sta. Pap. No. 147. Southeast. For. Exp. Sta., Asheville, NC. 9 p.

West, Neil E. 1968. Rodent-influenced establishment of ponderosa pine and bitterbrush seedlings in central Oregon. Ecology 49(5):1009-1011.

West, Neil E. and M. A. Hassan. 1985. Recovery of sagebrush-grass vegetation following wildfire. J. Range Manage. 38:131-134.

West, N. E. and R. W. Wein. 1971. A plant phenological index technique. BioScience. 21:116-117.

Whitford, Walter G. 1986. Decomposition and nutrient cycling in deserts, p. 93-117. IN Walter G. Whitford (ed.). Pattern and process in desert ecosystems. Univ. New Mex. Press, Albuquerque.

Whittaker, Robert H. 1975. Communities and ecosystems. MacMillan Publishing. Co., New York. 385 p.

Wiens, John A., John T. Rotenberry, and Beatrice Van Horne. 1986. A lesson in the limitations of field experiments: Shrubsteppe birds and habitat alteration. Ecology 67:365-367.

Wilcox, B. A. 1980. Insular ecology and conservation, p. 95-117. IN M. E. Soule and B. A. Wilcox (eds.). Conservation biology: An evolutionary -

ecological perspective. Sinauer Associates, Sunderland, MA.

Willson, M. F. 1974. Avian community organization and habitat structure. Ecology 55:1017-1029.

Wilson, Edward O. 1985. The biological diversity crises. BioScience 35:700-706.

Wolf, Michael L. and Joseph A. Chapman. 1987. Principles of furbearer management, p. 101-112. IN Milan Novak, James A. Baker, Martyn E. Obbard, and Bruce Malloch (eds.). Wild furbearer management and conservation in North America. Ontario Trappers Assoc., ON, Canada.

Wright, Henry A. 1970. A method to determine heat-caused mortality in bunchgrasses. Ecology 51(4):582-587.

Wright, Henry A. 1971. Why squirreltail is more tolerant to burning than needle-and-thread. J. Range Manage. 24(4):277-284.

Wright, Henry A. and Arthur W. Bailey. 1982. Fire ecology, United States and southern Canada. John Wiley and Sons, Wiley-Interscience Publication, New York. 501 p.

Wright, Henry A. and Carlton M. Britton. 1982. Fire in range and arid lands. Lesson Plan. IN Advanced Fire Management, Natl. Adv. Resour. Tech. Center, Marana, AZ.

Wright, Henry A., Francis M. Churchill, and W. Clark Stevens. 1976. Effect of prescribed burning on sediment, water yield, and water quality from dozed juniper lands in central Texas. J. Range Manage. 29:294-298.

Wright, Henry A. and James O. Klemmedson. 1965. Effect of fire on bunchgrasses of the sagebrush- grass region in southern Idaho. Ecology 46(5):680-688.

Wright, Henry A., Leon F. Neuenschwander, and Carlton M. Britton. 1979. The role and use of fire in sagebrush-grass and pinyon-juniper plant communities. USDA, For. Serv. Gen. Tech. Rep. INT-58. Intermt. For. and Range Exp. Sta., Ogden, UT. 48 p.

Wright, H. E., Jr. 1981. The role of fire in land/water interactions, p. 421-444. IN H. A. Mooney, T. M. Bonnicksen, N. L. Christensen, J. E. Lotan, and W. A. Reiners (eds.). Proc. conf. - Fire regimes and ecosystem properties. USDA, For. Serv. Gen. Tech. Rep. WO-26. Washington, D.C.

Wyant, James G., Richard D. Laven, and Philip N. Omi. 1983. Fire effects on shoot growth characteristics of ponderosa pine in Colorado. Can. J. For. 13:620-625.

Yarie, J. 1983. Environmental and successional relationships of the forest communities of the Porcupine River drainage, interior Alaska. Can J. For. Res. 13(5):721-728.

Yeo, Jeffrey J. 1981. The effects of rest-rotation grazing on mule deer and elk populations inhabiting the Herd Creek allotment, East Fork Salmon River, Idaho. M.S. thesis, Univ. Idaho, Moscow. 119 p.

Yoakum, James D. 1979. Habitat improvement, p. 132-139. IN Richard D. Teague, and Eugene Decker (eds.). Wildlife conservation: Principles and practices. The Wildl. Soc. Washington, D.C.

Yoakum, James D. 1980. Habitat management guides for the American pronghorn antelope. USDI, Bur. Land Manage. Tech. Note 347. Serv. Center, Denver, CO. 74 p.

Young, J. A. and R. A. Evans. 1978. Population dynamics after wildfires in sagebrush- grasslands. J. Range Manage. 31: 283-289.

Young, Richard P. 1986. Fire ecology and management of plant communities of Malheur National Wildlife Refuge, southeastern Oregon. Ph.D. thesis. Oreg. State Univ. 169 p.

Youngberg, C. T. 1981. Organic matter of forest soils, p. 137-144. IN Paul E. Heilman, Harry W. Anderson, and David M. Baumgartner (eds.). Forest soils of the Douglas-fir region. Wash. State Univ. Coop. Ext. Serv., Pullman.

Zasada, John C. 1971. Natural regeneration of interior Alaska forests - Seed, seedbed, and vegetative reproduction considerations, p. 231-

246. IN C. W. Slaughter, Richard J. Barney, and G. M. Hansen (eds.). Fire in the northern environment - A symposium. USDA, For. Serv. Pacif. Northw. For. and Range Exp. Sta., Portland, OR.

Zasada, John C. 1985. Production, dispersal, and germination of white spruce and paper birch and first-year seedling establishment after the Rosie Creek fire, p. 34-37. IN Glenn P. Juday, and C. Theodore Dyrness (eds.). Early results of the Rosie Creek fire research project, 1984. Agric. and For. Exp. Sta., Misc. Pub. 85-2. Univ. of Alaska, Fairbanks.

Zasada, John C. 1986. Natural regeneration of trees and tall shrubs on forest sites in interior Alaska, p. 45-73. IN K. Van Cleve, F. S. Chapin, III, P. W. Flanagan, L. A. Viereck, and C. T. Dyrness (eds.). Forest ecosystems in the Alaskan taiga. Springer-Verlag. New York.

Zasada, John C. 1989. Personal conversation with Melanie Miller.

Zasada, John C., M. Joan Foote, Frederick J. Deneke, and Robert H. Parkerson. 1978. Case history of an excellent white spruce cone and seed crop in interior Alaska: Cone and seed production, germination, and seedling survival. USDA, For. Serv. Gen. Tech. Rep. PNW-65. Pacif. Northw. For. and Range Exp. Sta., Portland, OR. 53 p.

Zasada, John C., Rodney A. Norum, Robert M. Van Veldhuizen, and Christian E. Teutsch. 1983. Artificial regeneration of trees and tall shrubs in experimentally burned upland black spruce/feather moss stands in Alaska. Can. J. For. Res. 13(5):903-913.

Zasada, John C. and George A. Schier. 1973. Aspen root suckering in Alaska: Effect of clone, collection date, and temperature. Northw. Sci. 47(2):100-104.

Zimmerman, G. T. 1988. Monitoring fire behavior and characteristics. Lesson plan. IN Fire Effects on Public Lands. Boise Interag. Fire Center, Boise, ID.

Zimmerman, G. Thomas. 1990. Personal conversation with Melanie Miller.

Zschaechner, Greg A. 1985. Studying rangeland fire effects: A case study in Nevada, p. 66-84. IN Ken Sanders and Jack Durham (eds.). Rangeland fire effects: A symposium. USDI, Bur. Land Manage., Idaho State Office, Boise.

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[1] The two publications by Frank Freese are no longer printed by the government, but have been reprinted under one cover by O.S.U. Bookstores, Inc., Oregon State Univ., Corvallis, 97331.

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CHAPTER CREDITS

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VII. Terrestrial Wildlife and Habitat - Loren Anderson

VIII. Cultural Resources - Dr. Richard C. Hanes

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