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Forest Ecology and Management 127 (2000) 1–18

Forest Ecology and Management

www.elsevier.com/locate/foreco

Solution of forest health problems with prescribed fire: are forest productivity and wildlife at risk?

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Received 19 November 1998; accepted 25 February 1999

Abstract

Advanced forest succession and associated accumulations of forest biomass in the Blue Mountains of Oregon and Washington and Intermountain area have led to increased vulnerability of these forests to insects, diseases, and wildfire. One proposed solution is large-scale conversion of these forests to seral conditions that emulate those assumed to exist before European settlement: open-spaced stands (ca. 50 trees per ha), consisting primarily of ponderosa pine (*Pinus ponderosa* Laws.) and western larch (*Larix occidentalis* Nutt.). We question how well presettlement forest conditions are understood and the feasibility and desirability of conversion to a seral state that represents those conditions. Current and future expectations of forest outputs and values are far different from those at presettlement times. Emphasis on prescribed fire for achieving and maintaining this conversion raises questions about how well we understand fire effects on forest resources and values. We consider here potential effects of prescribed fire on two key aspects of forest management—productivity and wildlife. Use of large-scale prescribed fire presents complex problems with potential long-term effects on forest resources. Before implementing prescribed fire widely, we need to understand the range of its effects on all resources and values. Rather than attempting to convert forests to poorly described and understood presettlement seral conditions, it would seem prudent to examine present forest conditions and assess their potential to provide desired resource outputs and values. Once this is achieved, the full complement of forest management tools and strategies, including prescribed fire, should be used to accomplish the desired objectives. We suggest a more conservative approach until prescribed fire effects are better understood.

Keywords: Biomass; Decomposition; Down wood; Forest floor; Fuels; Nutrients (soil and biomass); Snags

1. Introduction

The Blue Mountains Province of the interior Pacific Northwest is the focus of intense local, regional, and national concern over widespread decline in health of forests (Gast et al., 1991; Wickman, 1992; Everett et al., 1993; Swetnam et al., 1995). With exclusion of fire and introduction of white pine blister rust (*Cronartium ribicole* J.C. Fisch.), the former northern forests of western white pine (*Pinus monticola* Dougl.), ponderosa pine (*P. ponderosa* Laws.) and western larch (*Larix occidentalis* Nutt.) were invaded by shade-

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PII: S0378-1127(99)00114-0

tolerant coniferous tree species (Jurgensen et al., 1997). The resulting composition and structural changes predisposed these forests to attack by insects and diseases, which otherwise play positive roles in ecosystem function (Jurgensen et al., 1997), and to fire (Agee, 1993; Hessburg et al., 1994). This problem is not new to the region—the outbreak of Douglas-fir tussock moth (*Orgyia pseudotsugata* McDunnough) in the 1950s and 1970s suggested everything was not right with these forests. Wellner (1978) emphasized the pervasive consequence of fire control on plant succession. He writes: "Forests, when uninterrupted by management activities such as logging move more rapidly toward climax conditions than in the days before fire control." Selective harvest and thinning removed seral species, such as ponderosa pine and western larch, leaving a residual stand of shade-tolerant species such as Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) and grand fir (*Abies grandis* (Dougl.) Lindl.) (Wellner, 1978). Succession favoring these species has also increased the supply of host trees for the Douglas-fir tussock moth and western spruce budworm (*Choristoneura occidentalis* Freeman) (Stoszek, 1978; Wickman, 1992). Although periodic outbreaks of these defoliators have been documented for the past 300 years, severity and frequency have increased in the 20th century (Swetnam et al., 1995).

Resource managers and scientists were sensitized to the problem of advanced forest succession and widespread supply of host trees (Douglas-fir and grand fir) by the time the western spruce budworm outbreak began in the early 1980s. One consequence of recognizing the forest health problem in the interior Pacific Northwest has been a recommendation to restore fire to its presettlement role of maintaining forest stands in a seral condition (Brown and Arno, 1991; Gast et al., 1991; Richards, 1992; Everett et al., 1993; Mutch et al., 1993). Conversion to seral species, such as ponderosa pine and western larch, is seen as one way to reduce the proportion of host species for defoliating insects (Mason and Wickman, 1988; Wickman, 1992). Prescribed fire has been proposed as the primary means to alleviate accumulated woody fuels and overstocked stands that make these forests so vulnerable to wildfire. Mutch et al. (1993) conclude that reintroducing fire on a large scale is the most effective way to restore forest health. They believe a ten-fold increase in prescribed fire will be needed to restore the forests in the Blue Mountains. They proposed a shift from the way we now perceive and govern outputs, such as smoke particulates and sediment load in streams, and the way in which we protect values, such as wildlife cover and scenery.

Emphasis on fire as a principal management tool to restore health to the Blue Mountains raises several questions about our understanding of how fire affects forest ecosystems. Although information on effects of both wild and prescribed fire on various components of forest ecosystems is available, we are concerned that the information is not being fully utilized in planning prescribed burning for management purposes. We maintain that managing for improved health of forests in the Blue Mountains (or any forest) that focuses on prescribed fire as a primary tool, needs to use fire plans that have considered how fire affects *all* of the important resources and values. Certainly, fire affects nutrient pools, integrity and function of the forest floor, plant species composition, soils, wildlife, water yield and quality, air quality (including carbon loading of the atmosphere), long-term forest productivity, and likely many other components of forest ecosystems.

Interest in large-scale use of fire to restore it to its perceived historical role in Western forests coincides with worldwide concern about forest productivity (Malkonen, 1975; Kimmins, 1977; Ballard and Gessel, 1983; Grier et al., 1989; Vose and Swank, 1993; Monleon et al., 1997). The International Union of Forestry Research Organizations (IUFRO) considers forest productivity of key importance and it is devoting a substantial part of its effort toward solving problems of forest productivity. Concern is directed at establishing the relations between nutrient losses associated with management strategies and changes in forest productivity (Freedman, 1981).

In this paper, we focus on the effects of prescribed fire on forest productivity and wildlife resources. Neither subject has received in-depth consideration in reports proposing prescribed burning as the primary means of solving forest health problems (Brown and Arno, 1991; Gast et al., 1991; Wickman, 1992; Everett et al., 1993; Mutch et al., 1993). Our objective is to suggest that a broader array of resource questions be considered before prescribed burning is implemented. We think the objectives of prescribed burning must be clearly defined and realistic estimates stated for outcomes for all affected resources. If the objective is to restore forest health (Wickman, 1992; Mutch et al., 1993), then we suggest that forest productivity, wildlife, biodiversity, and other resources and values are as much a part of the forest health equation as are the structure of a forest stand and its tolerance to fire. Thus, management aimed at returning forests to an open, seral condition should be carefully evaluated from the perspective of all the key resources and values. Can objectives for producing wood fiber, as well as goals for wildlife habitat, biodiversity, soil protection, and water and air quality be simultaneously met? We think the answer is yes. But, our thinking must go beyond factors governing how a given controlled burn will affect the forest stand, the accumulated fuel load, and protecting life and property.

We emphasize the Blue Mountains of eastern Oregon and Washington because we have more experience with these forests, and this area was where the Northwest forest-health problem first received widespread attention. Considerations developed in this paper, however, should apply to many temperate zone forests of the United States.

2. An open, seral forest as a management goal

Before addressing issues related to implementing prescribed burning on a large scale, we examine the basis for developing management goals for stands now densely stocked by shade-tolerant species, such as grand fir, now considered unhealthy and at risk from insects, diseases, and wildfires. The strategy (Mutch et al., 1993) is to return these dense, overstocked stands to open, parklike stands dominated by ponderosa pine and western larch. The strategy would be achieved by harvest, thinning, mechanical residue reduction, and prescribed fire. Short-interval (7–10 years) prescribed fire is the primary tool recommended for maintaining subsequent stand conditions.

Tree spacing and species composition as described by early immigrants and settlers, thought to persist through the late 1800s, are perceived by some authors (Wickman, 1992; Covington and Moore, 1994; Covington et al., 1997) as the goal. Certainly the documented accounts of immigrants and settlers may accurately represent the forest conditions observed, but how extensive and complete were these observations? As Hoover (personal communication, M.D. Hoover, Rocky Mountain Research Station (retired)) observed,

> It may be worth noting that travelers seek open stands. Few trails pass through dense stands by choice. Naturally, early wagon passengers and horsemen saw open stands. Also, photographers and artists favored more open forests and avoided dense stands for their illustrations. This could bias our impression of past conditions.

Questioning recommendations that forests be returned to 'presettlement' successional status seems important. Following Hoover's reasoning and pondering literature on the subject, we question how well presettlement forest conditions are understood. How pervasive was the influence of fire throughout forests of the Blue Mountains? Hall (1976) indicates that the ponderosa pine/pinegrass (*Calamagrostis rubescens* Buckl.) association was burned by surface fires at 7–10-year intervals. Of 22 habitats now dominated by grand fir and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) listed by Johnson and Clausnitzer (1992), however, only three were historically seral ponderosa pine that were burned by periodic surface fires (personal communication, Dr. F.C. Hall, Pacific Northwest Region, USDA Forest Service). In stands dominated by grand fir, Douglas-fir, and western larch, Hall (1973) determined that dominant trees were 120 to >200 years old. Periodic surface fires would have eliminated firs and resulted in seral stands of western larch and ponderosa pine. Hall's findings suggest that stand-replacement fires predominated in those stands and that periodic surface fires mainly affected the true ponderosa pine associations. Heyerdahl (1997) constructed fire history from the late 1600s to the present, using fire scars and clusters of seral cohorts in northern and southern Blue Mountains. High frequency of recurrence, low severity fires historically occurred in the dry grand fir, Douglas-fir, and ponderosa pine forest associations. In mesic grand fir and subalpine fir forest associations, fires were historically of low recurrence frequency and moderate or high severity.

Characterizations of presettlement forests allude to their openness and give qualitative descriptions of stand structure (Cooper, 1960; Biswell, 1973; Wickman, 1992; Covington and Moore, 1994); an exception is White's (White, 1985) analysis of a ponderosa pine natural area. He analyzed age-structure and mapped stem spatial distribution of 268 trees (106–410 years old) that originated prior to European settlement. Covington and Moore (1994) attempted to reconstruct forest floor accumulation, forage production, streamflow, and other resource information from simulation models. But what do we know about how these systems actually functioned—their biogeochemistry? Specifics are lacking (Bonnickson and Stone, 1985). At this stage in maturity of the forest sciences, we should be able to describe—more precisely than merely 'presettlement'—the conditions constituting a healthy forest. Bonnickson and Stone (1985) make the case for developing quantitative standards for natural structure and function of ecosystems as a basis for judging effectiveness of management practices in national parks. In a similar vein, Johnson and Mayeux (1992) suggest that few, if any, truly stable and natural plant assemblages exist, and that we should be bold enough to shape and synthesize new ecosystems, even in 'natural' environments.

Following-up on these thoughts, perhaps a science-based approach that looks quantitatively at the various components, values and functions of ecosystems may be the key to describing healthy forest ecosystems. The status (condition) of any one resource may not be maximized in the 'healthy forest', however. Sacrifices in terms of productivity may be likely in most vegetation classes—trees, forbs, and shrubs. Widely spaced trees of slow-growing species will likely be less productive than a wider array of species (including Douglas-fir and grand fir) with higher densities (Hall, 1976; Johnson and Clausnitzer, 1992). In a study of responses of ponderosa pine to thinning at several Western locations, Oliver and Edminster (1988) indicate that stands thinned to 10 m^2 basal area per hectare to achieve open-spaced trees added 1.2 m^3 of wood annually compared to 1.9 m^3 in stands thinned to 25 m^2 basal area per hectare. Although individual trees grew faster in more open stands (as expected from results of numerous thinning studies), total volume production was clearly reduced. This information provides a clue to productivity expectations when ponderosa pine stands are converted to open, parklike stands. From the standpoint of other resources, what is the effect of 10 m^2 vs. 25 m^2 of timber basal area? From a wildlife perspective, what populations of large wild herbivores, such as deer and elk, can be supported as timber basal area is reduced? How will threatened and endangered or sensitive wildlife species that prefer successionally mature forested habitats respond?

Alleviation of insect and disease problems has been cited as one of the primary reasons for converting mixed conifer forests to dominance of seral tree species, primarily ponderosa pine and western larch. We wonder how well the insect and disease problems associated with this conversion are understood. Both tree species are affected by numerous insect and disease agents (Schmidt and Shearer, 1990; Oliver and Ryker, 1990).

The next question is about the feasibility of returning these stands to a condition that emulates presettlement species composition and spacing (even if we knew what they were). Emerging ecological theory on community thresholds, stable states, and succession (Laycock, 1991; Tausch et al., 1993) suggests that this task may not be simple. Nearly 100 years of fire exclusion, possible climate changes, and past management practices may have caused these communities to cross thresholds and to reside now in different steady states. If so, returning to some previous condition may be difficult to achieve, expensive to maintain, or both. Baker (1992) is straightforward in his conclusion that "landscapes that have been altered by settlement and fire suppression cannot be restored using traditional methods of prescribed burning, which will simply produce further alteration."

Tausch et al. (1993) are helpful in developing a perspective on the natural range of variability of forests of the Blue Mountains. They conclude that plant communities are unique at each location and difficult to define precisely. Climate and climate change have been key factors in the responses of individual plant species and in the composition of plant communities. Their suggestion that we do not have the knowledge to describe the interaction between ecosystems and climatic change seems highly applicable to the Blue Mountains. Our present view of the natural range of variability is an obscure 'snapshot' relative to the span of time since the last glaciation and since the eruption of Mt. Mazama ca. 6600 years bp (Baldwin, 1964).

Tree-ring analysis by Fritts et al. (1979) raises further doubt about the validity of the narrow window of time (1850–1900) used by Caraher et al. (1992) to assess the natural range of variability of forest ecosystems in the Blue Mountains. Even since 1602, several climatic shifts and associated shifts in tree composition have occurred in the interior Pacific Northwest. Pollen assemblages examined by Fritts et al. (1979) showed three periods since 1602 when ponderosa pine and lodgepole pine decreased. These responses were apparently related to higher winter precipitation as reconstructed by Fritts et al. (1979). Western white pine, representing more mesic conditions, either displayed an opposite response or remained constant.

3. The blue mountain forests: physical and biological setting

In order to understand the potential ecological consequences of reintroducing fire on a large scale in the Blue Mountains, understanding the physical setting and the successional status of the vast mixed conifer type of this locale is helpful, as is some knowledge of the factors that limit productivity.

Soils of much of this region developed from Mazama volcanic ash and are juvenile with poorly defined horizons. Geist and Cochran (1991) describe the 50–60-cm ash profiles of eastern Oregon as light colored, of silt-loam texture, and weakly structured. Ash generally overlies buried soil derived from Columbia River basalt that enveloped the area from 53 to 17 million years ago (Baldwin, 1964). The buried soil is typically silty clay to clay loam in texture (Geist and Cochran, 1991). Total and available nitrogen and sulfur are typically limiting in soils developed from volcanic ash (Tiedemann and Klock, 1977; Geist and Strickler, 1978; Tiedemann et al., 1998). Precipitation ranges from ca. 20 cm at Pendleton, OR (700 m elevation) to 140 cm at the High Ridge Barometer Watersheds at 1700 m elevation (NOAA, 1984; Fowler et al., 1979). Until recently, water was considered the primary limiting factor in these soils, but a closer examination of limiting factors by Riegel et al. (1991) shows water and nutrients (in their study, only N) may be about equally limiting to understory growth. Similar limitations likely would apply to growth of trees.

Forested areas of eastern Oregon span a gradient from the warm-dry western juniper (*Juniperus occidentalis* Hook.) zone to the cool-moist subalpine fir/ Engelmann spruce (*Picea engelmannii* Parry) zone. Focus of the forest health problem is the mixed conifer type that occupies mid- to high-elevation areas (1000–1700 m). These sites typically have a mix that may include as many as six conifer species. Sites that support lodgepole pine (*Pinus contorta* Dougl.), Douglas-fir, ponderosa pine, western larch, Engelmann spruce, and grand fir are not uncommon. At higher elevations, >1500 m, subalpine fir becomes part of the species mix. Mixed conifer sites often have grand fir >120 years old with abundant grand-fir regeneration.

4. Forest succession: biomass and nutrient accumulation

Several authors (Stoszek, 1978; Wellner, 1978; Wickman, 1992; Mutch et al., 1993; Swetnam et al., 1995) have suggested that effective fire control, together with selective removal of large trees of seral species has resulted in a shift in dominance to shade-tolerant Douglas-fir, and grand fir. From a forest-succession perspective, this shift may be a natural sequence of events for these forests. A consequence of this advance in succession was increased accumulation of aboveground biomass and nutrients in standing live trees, standing dead trees (snags), downed wood (boles and branches), and the forest floor (Odum, 1969; Rodin and Bazilevich, 1967; Major, 1974). Hamilton and Wykoff (1988) used the Stand Prognosis Model (Stage, 1973) to predict tree productivity at various stages of stand development in the northern Rocky Mountains. Up to age 60, stands managed to favor intolerant tree species were more productive than those favored tolerant species. Between age 60 and 150 years, stands that managed to favor tolerant species were more productive. In the Blue Mountains, stands dominated by ponderosa pine were lowest in productivity (1.4–3.5 m^3 ha^{-1} $year^{-1}$) among those measured by Johnson and Clausnitzer (1992). Productivity of stands dominated by Douglas-fir and grand fir were substantially greater (3.5 to >8.3 m^3 ha^{-1} $year^{-1}$). On Meeks Table Research Natural Area in central Washington (Tiedemann and Klock, 1977; data on file, Tiedemann), basal area was nearly twice as great in a mixed conifer stand (66 m^2 ha^{-1}) as in an adjacent old-growth ponderosa pine stand (39 m^2 ha^{-1}); forest floor was 31% greater in the mixed conifer stand. Large ponderosa pine in the mixed conifer stand (some alive and some dead) indicated that ponderosa pine was seral to the mixed conifer stand. To our knowledge, these data are the only ones available for comparing old-growth ponderosa pine and mixed conifer on similar sites. These comparisons, although limited in scope, lend support to our hypothesis that biomass in forest communities of the interior Northwest increases with advancing succession.

Information on nutrient accumulation in aboveground biomass for interior Northwest stands is limited. Brown (1977) studied biomass and nutrient distribution of two stands in eastern Washington; one was mixed conifer and the other was dominated by Douglas-fir. In the mixed conifer stand, 39% of N in the system was contained in aboveground biomass components (trees, 24%; forest floor, 15%). Understory was a minor component. In the Douglas-fir stand, 22% of the site N was in aboveground components, about equally distributed between tree components and the forest floor. Although the two sites are not directly comparable from a successional standpoint, the mixed conifer was likely more advanced than the Douglas-fir stand. Brown's (Brown, 1977) results appear to confirm our concern that the proportion of a site's total nutrient capital in a vulnerable aboveground position increases with advancing succession.

5. Some thoughts about burning the forest floor

Although we focus on forest floor because of its acknowledged importance to forest ecosystems, we allude briefly to coarse woody debris (CWD), which includes forest detritus other than fine litterfall. In contrast to litterfall, which occurs annually following leaf senescence, and immediately becomes forest floor, CWD arises mostly from disturbance, varies greatly in space and time, and is low, but variable, in rate of decay and nutrient content, except organic C (Harmon et al., 1986; Arthur and Fahey, 1990; Busse, 1994). Initially, CWD appears as loosely arranged, scattered debris above the forest floor, or as snags. If it escapes fire, much CWD may be incorporated eventually into the forest floor (Jurgensen et al., 1997). Although CWD until recently, has been neglected in forest ecosystem studies, its importance to physical, chemical and biological functioning of forests, including nutrient cycling, is now being recognized (Maser and Trappe, 1984; Harmon et al., 1986; Jurgensen et al., 1997; Hagan and Grove, 1999).

5.1. Relevance of structure and function of forest floor

The forest floor is a key component in the biology of forest ecosystems, but it is probably more affected and more likely to be lost by fire than any other component of forest ecosystems (Page-Dumroese et al., 1991). According to McNabb and Cromack (1990), "The most important criterion for reducing nutrient losses from prescribed burning is to minimize the loss of the forest floor." With low intensity wildfires and, in many prescribed fires, the forest floor may be the only part of the forest to burn. If forest floor is viewed only as the annual accumulations of dead plant and animal remains, loss of forest floor may seem inconsequential, even when fire is used frequently in pursuit of short-term goals of productivity or naturalness (Sackett et al., 1993; Covington et al., 1997). But, when viewed in terms of the complex chemical, physical, and biological processes that take place during decomposition of these dead organic resources (Swift et al., 1979), loss of forest floor by burning does have consequences that warrant careful consideration.

Decomposition in the forest floor performs two major functions—mineralization of nutrients and the formation of soil organic matter (Swift et al., 1979); both are key to long-term ecosystem productivity and stability. When the forest floor is burned too frequently, nutrient replenishment and organic matter formation are diminished. Other roles and attributes ascribed to the forest floor are that it serves as the essential linkage between nutrient cycling processes, both above- and belowground; provides protection to the soil surface and improves soil architecture; facilitates water absorption and retention; and moderates soil temperatures (Kittredge, 1948; Harvey et al., 1976; Wells et al., 1979; Page-Dumroese et al., 1991).

In view of the extensive literature on forest floor, its organization, structure, and properties are well known for most forests (Kittredge, 1948; Hoover and Lunt, 1952; Soil Survey Division Staff, 1993) and explain how loss of forest floor can be costly to its functional processes when fires are too intense or too frequent. The dilemma, in terms of the forest floor alone, is not "burning or no burning"; it involves figuring out when and how to burn, and the minimum interval between burns without unacceptable risks to productivity. Clearly, the cost of burning to forest-floor resources is less when the upper layer is burned than when lower layers are burned. This follows from the steep gradient in most forest-floor properties (e.g. decomposition activity, microbial biomass, concentration and mass of nutrients) with increasing forest-floor depth. Thus, if the goal of management is to minimize losses of these resources during a prescribed burn, fire should be planned when the upper layer of forest floor is dry enough to carry a fire, but lower layers are wet enough not to be consumed. Though logistically difficult, this can be achieved (Klemmedson et al., 1962). If these conditions are not achievable, when the priority for burning is otherwise high, the cost of burning the entire forest floor can be lowered by extending the time of recovery before the next planned burn. This also would apply when burning is planned to expose mineral soil for tree regeneration.

5.2. Nutrient content

With maturity and later successional stages, the forest floor becomes an increasingly significant pool of nutrients in the cycling process (Rodin and Bazilevich, 1967; Odum, 1969; Page-Dumroese et al., 1991). In Western-montane forests, total N in the forest floor ranged from 128 kg ha^{-1} for ponderosa pine to 787 kg ha^{-1} in cedar/hemlock stands (Page-Dumroese et al., 1991). Forest floors of five, successionally mature, mixed conifer stands in the Blue Mountains contained 680, 108, and 68 kg ha^{-1} of N, P, and S, respectively (Tiedemann et al., unpublished manuscript). For an Arizona ponderosa pine stand, Klemmedson (1975) reported 291 kg ha^{-1} of N in the forest floor, a small amount compared to soil N (5200 kg ha^{-1}), but not much smaller than that in the standing trees (415 kg ha^{-1}). Because this forest floor was only 4 cm thick, nutrients here were more highly concentrated than elsewhere in the ecosystem, and more readily available, that is, they had lower mean residence time than those in the soil component (Paul, 1970; Campbell, 1978). As the forest floor thickens in cooler, moister forests, its importance as a concentrated nutrient pool becomes even more important.

5.3. Decay and nutrient cycling in forest floors

Fire exclusion from forests is often said to result in steady accumulation of litter (Covington and Sackett, 1984), and stagnation of decomposition and nutrient recycling processes (Biswell, 1973; Covington and Sackett, 1984, 1986, 1990). As a remedy for perceived stagnation in decomposition and nutrient cycling, frequent or repeated burning has been suggested to release nutrients, increase N availability and improve productivity (Covington and Sackett, 1986, 1990; Covington et al., 1997).

In reality, few, if any, temperate forests have nutrients literally tied up or bound in the forest floor. With little or no disturbance, forest floors are steady-state systems with the mineral soil beneath. The annual rate of additions of organic material to the forest floor equals losses (Jenny et al., 1949; Olson, 1963) through evolution of gases and migration of soluble and dispersed humic substances into the mineral soil. In practice, Klemmedson et al. (1962) found close agreement with this relation for a second-growth California pine forest: the annual transfer of N (12.4 kg ha^{-1}) from the forest floor and loss rate ($k = 3.28\%$), calculated experimentally, agreed closely with N content of annual litterfall (13.7 kg ha^{-1}) and the loss rate ($k = 2.95\%$) calculated by steady-state considerations (Jenny et al., 1949; Olson, 1963).

One reason for the perception that forest floor is steadily accumulating in the absence of fire may be that fine forest detritus has been classified differently for fuel characteristics than it is in describing forest floor as a component of the soil–plant system. Woodard (1977, 1993) includes in a litter category of 'fuels,' the L or O_i layer of forest floor together with branches up to 7.6 cm, yet branches of this size decay much more slowly than leaves or needles of the L layer. Failure to discern these differences may give an observer the impression that litter is accumulating and decomposition stagnating.

The perception that litter is accumulating probably also comes from the inherently low decay rates of forest floors of coniferous forests (1–12%), especially in semi-arid, alpine and Arctic regions (Jenny et al., 1949; Olson, 1963; Edmonds, 1979); decay of CWD is even slower (Harmon et al., 1986).

5.4. Effects of fire on forest-floor nutrients

Fire alters physical, chemical, and biological properties of the forest floor and interrupts or modifies the orderly transfer of nutrients from the forest floor to the soil. Burning oxidizes the forest floor, resulting in direct loss of elements to the atmosphere as volatilized compounds—when critical temperatures are reached—or as particulates carried away in smoke or released as oxides to the ash layer (Tiedemann, 1981; Woodmansee and Wallach, 1981; Raison et al., 1984; McNabb and Cromack, 1990; DeBano, 1991; DeBano et al., 1998). In some forests, leaching loss of nutrients deposited in the ash is possible (Stark, 1977), when precipitation is adequate for percolation below the root zone, and when capacity of vegetation for uptake and/or soil nutrient storage capacity are insufficient to retain nutrients (cations and anions) carried into the soil from ash after fire (Tiedemann et al., 1979).

Nitrogen, S, P and K are all susceptible to volatilization loss by burning (Klemmedson, 1976; DeBano and Conrad, 1978; Raison et al., 1984; Tiedemann, 1987). Nitrogen is lost at temperatures as low as 200°C (DeBano, 1991); Raison (1979) reported thermal decomposition of nitrite and nitrate >150°C. At temperatures as low as 375°C, loss of S can be substantial (Tiedemann, 1987). As temperatures approach 800°C, virtually all N and S are volatilized. At 775°C, phosphorus (P) and potassium (K) are volatilized. Loss of P can be ecologically significant; this may be expected if its loss from burned sites is long-term because of low replacement rates (Raison et al., 1984; Wienhold and Klemmedson, 1992). Oxides of calcium (Ca) and magnesium (Mg), and nonvolatilized portions of N, S, P, and K are deposited as ash in largely available forms (Woodmansee and Wallach, 1981; Tiedemann, 1981; DeBano et al., 1998). In any given fire, spatial variation in site configuration, fuel loading, fuel moisture, and weather will influence fire intensity and burning temperatures (Swift et al., 1993). As burning temperatures vary spatially, so too will nutrient losses. Nutrients, or portions of them, that escape volatilization or convection to reside in the ash or surface soil are readily available, hence vulnerable to leaching and erosion (Tiedemann et al., 1979; Wells et al., 1979; Wienhold and Klemmedson, 1992), or to loss by repeated burning (Wright and Hart, 1997).

Since N is usually limiting in forest and grassland soils, increase in N availability after fire is an advantageous result of prescribed burning (Woodmansee and Wallach, 1981; Covington and Sackett, 1986, 1992). Increase in N availability is not always observed after fire, however, (Vance and Henderson, 1984; Ojima et al., 1988; Monleon et al., 1997), and it is short-lived, usually lasting only a year or so (Kovacic et al., 1986; Monleon et al., 1997). The increase results from direct conversion to available forms (Kovacic et al., 1986), mineralization (Ojima et al., 1988; Covington and Sackett, 1992), or mobilization by microbial biomass through the fertilizing effect of ash nutrients and improved microclimate (Koelling and Kucera, 1965; Hulbert, 1969; Ojima et al., 1988).

5.5. Repeated burning of the forest floor

Although short-term increased N availability is used as a justification for frequent, repeat prescribed burning (Covington and Sackett, 1986, 1992; Covington et al., 1997), this practice, if carried out long-term, may risk future forest productivity. Below, we cite results of studies of repeated annual or two-year burning. Unfortunately, studies have not been conducted for intermediate intervals (5–15 years), so we can only surmise costs and benefits for burning on this schedule.

Recent studies by Binkley et al. (1992) have shown reduced pools of C, N, and S in the forest floor after 30 years of annual burning. From a review of 20 years of the two-year-interval burning in ponderosa pine, Wright and Hart (1997) concluded that N had been substantially depleted in forest floor and surface soil. Monleon et al. (1997) found that a surface fire in ponderosa pine resulted in decreased concentration of total surface soil C, N, and inorganic N after four years. Mineralization of N was reduced, even after 12 years, indicating reduced substrate quality. In oak–hickory forests, annual and periodic burning over 30 years negatively influenced N availability (Vance and Henderson, 1984), largely through the effects on substrate quality that lowered rates of N mineralization. Ojima et al. (1994) reported similar findings from repeated annual burning of tallgrass prairie.

Results of long-term studies described here point out potential problems of repeated burning when long-term costs to the ecosystem of attempts to capitalize on short-term gains (such as improved N availability) have not been considered or perhaps are not understood. Earlier (Klemmedson and Tiedemann, 1995), we alluded to the problem of focusing too much attention on nutrient availability, without monitoring other critical parts of the nutrient regime when effects of prescribed burning are evaluated. Nutrient cycles are indeed complex. Hence, when the focus of prescribed burning is narrow (for example, opening the stand, improving N availability), the likelihood is high of a false sense of success from one or two positive results, when negative results for less obvious parameters (such as labile soil C and N pools, and microbial activity in the forest floor and soil) may have escaped attention, only to appear years later in more obvious expressions of negative results, such as declining long-term productivity. Studies of Ojima et al. (1994) are relevant: their findings, using a broad approach that focused on internal biogeochemical dynamics of tallgrass prairie in response to annual burning, offer insight to understanding responses to the long-term, short-interval burning studies described here. In the short-term, fire in the prairie enhanced microbial activity, increased production above- and belowground, and increased N use efficiency. But in the long-term, repeated annual burning resulted in lower inputs of C and N to the labile pool, higher C : N ratios of organic matter (reducing quality of the organic matter), lower microbial biomass, and lower N availability. Because of compensating shifts in C allocation, plant N use efficiency, and species adaptation, production in the tallgrass prairie has not been diminished (Ojima et al., 1994). The tallgrass prairie appears to be unique in this respect, however; we have not seen evidence for such adaptive shifts in forest systems to effects of repeated burning on the soil C and N pool described by Ojima et al. (1994).

Combustion of forest fuels invariably involves loss of nutrients, depending on burning conditions. Losses of N documented from prescribed burning are of chief concern. Little and Ohmann (1988) measured N losses of up to 666 kg ha^{-1} from forest floor during burning of logging residues. Loss of N was directly proportional to consumption of organic material; others (Raison et al., 1984; Vose and Swank, 1993) report similar findings. Borchers et al. (1993) estimated that 46% of the N stored in trees, the surface soil, and forest floor was lost during clearcutting and burning in southwestern Oregon. They concluded that N lost would not likely be replenished by the end of the 80–100-year rotation. In central Oregon, burning consumed as much as 60% of the forest floor biomass (Landsberg, 1992) and resulted in a loss of 414 kg ha^{-1} of N (Shea, 1993; cited by Monleon et al., 1997). Monleon et al. (1997) also did not observe the increase in N-mineralization and available N after burning as was reported by Covington and Sackett (1992) and others.

6. Effects of prescribed fire on forest productivity

Long-term productivity is a concern in developing strategies to solve the forest-health problem (Gast et al., 1991; Wickman, 1992; Everett et al., 1993). Objectives for achieving sustainable productivity have not been well defined for Western forests, however, and existing guidelines are vague. Everett et al. (1993) suggest that forest managers define desired future stand conditions and focus management efforts on achieving them. Any prudent plan should describe management goals in terms of forest productivity, biodiversity, wildlife habitat, and other resource outputs and values.

A primary concern whenever prescribed fire is used in forest management is loss of nutrients and impaired site productivity. This concern increases with changes in nutrient status that accompany successional advancement of forest systems in the absence of periodic fire. These changes usually involve increased accumulation of nutrients above the ground, much of it in the forest floor, and raise concern about the fate of these nutrients with careless use of fire or failure to consider fuel nutrients in fire plans. If sites that can be burned are treated without harvest, much of the nutrient capital accumulated in the forest floor is vulnerable to loss. If sites are harvested and residues are burned, not only will nutrients removed in trees be lost, but also—potentially—much of the nutrient pool in slash and forest floor, depending on burning conditions. Thus, the potential to adversely affect long-term site productivity is always present.

Evidence of reduced productivity is shown in the simulation model developed by Keane et al. (1990). Their 200-year simulation model compares development of basal area of ponderosa pine, western larch, and Douglas-fir under regimes of no fires with basal areas of the same species under fire intervals of 10, 20, and 50 years. At a fire interval of 10 years, the basal areas of ponderosa pine and western larch were predicted to decline by 50% or more in 200 years. Reductions of basal area of both species were predicted at the 20-year interval, but not as dramatically as with the 10-year interval. Under the 50-year interval, basal area of ponderosa pine and Douglas-fir both increased and that of western larch declined. The model indicated that, in the absence of fire, basal area of Douglas-fir would increase steadily to the year 200. Although basal area of ponderosa pine and western larch declined, the total basal area predicted for the site was greater (ca. 70 m^2 ha^{-1}) than that with any other simulation. The 50-year fire-interval simulation provided the next greatest basal area of about 50 m^2 ha^{-1}.

Landsberg (1994) provides the most comprehensive assessment of the effect of prescribed fire on forest productivity. In a review of more than 50 studies of the effects of prescribed fire on tree growth in the genus *Pinus*, she concluded that growth response can be affected by many factors: species, stand characteristics, tree characteristics, and burning conditions. The consensus of the studies, however, was that tree growth decreased after prescribed burning because of injury to crowns, roots, or both.

Concern for effects of burning on productivity was expressed as early as 1924 in a paper by Show and Kotok (1924) for pines and associated tree species in California. Powers (1991) concludes that productivity of forests has declined because of substantive losses of surface organic matter and declines in soil porosity as a consequence of harvest activities and burning. Boyer (1987) reported that periodic burning of longleaf pine (*P. palustrus* Mill.) over a 10-year period for understory hardwood control reduced pine growth, regardless of season of burning.

Reasons cited for reduced productivity after prescribed burning vary. Landsberg (1994) summarizes several reasons: direct injury to tree stems, crowns, and roots; reduction in microorganisms such as mycorrhizae, with concurrent reductions in nutrient availability; reduced photosynthetic capacity; and changes in carbon allocation.

The evidence indicates that losses from the forest-floor nutrient pool associated with prescribed burning can impair long-term productivity (Grier et al., 1989; Landsberg, 1992; Klemmedson and Tiedemann, 1995). The relation between fire-induced changes in the nutrient status of the forest floor and the actual productivity of the residual stand has not been established. Vose and Swank (1993) conclude that major pools of nutrients in woody material and the forest floor dictate a fire management strategy that places a high priority on maintaining an intact forest floor. They advise a balance between the desire to reduce logging slash and competition while minimizing forest-floor consumption. Observed reductions in growth of ponderosa pine after prescribed burning in central Oregon (Cochran and Hopkins, 1991; Landsberg, 1992) may be attributed to changes in the nutrient status of the forest floor/soil system (Monleon et al., 1997). They observed reduced mineralization of N in N-poor ponderosa pine stands in eastern Oregon for up to 12 years after burning and concluded that this reduction may explain the observed pattern of long-term productivity decrease in these stands.

7. Potential effects of prescribed burning on wildlife

The consequences of large-scale prescribed burning on wildlife in the Pacific Northwest are largely unknown because studies have been limited to investigating the effects of small prescribed burns on specific species for a relatively short time after burning. Prescribed burning may not always be compatible with other management objectives incorporating timber harvest, road building, recreation, and wildlife populations. The potential effects of prescribed burning on a landscape scale should be examined carefully to determine if the changes caused by prescribed burning are compatible with other management objectives for wildlife. Some of the more obvious potential consequences of large-scale prescribed fire are described below.

Historically, in the Blue Mountains most short-interval surface fires were in ponderosa pine associations (Hall, 1976). Grand fir, subalpine fir, and western larch associations were primarily subjected to long-interval (i.e. 150–200 years), stand-replacement fires (personal communication, F.C. Hall, Pacific Northwest Region, USDA Forest Service). Much of the prescribed burning in the Blue Mountains and recommended in the draft Columbia River Basin Environmental Impact Statement (EIS) is aimed at reducing fuels in ponderosa pine stands and converting mixed conifer stands to seral ponderosa pine and western larch. Structural changes resulting from these types of burns would significantly affect some wildlife by reducing the amount of down wood, reducing numbers of older snags, and changing the vegetative species composition of the stands.

7.1. Down wood

The loss of down wood in forested stands through the use of prescribed fire may affect some wildlife species detrimentally, although effects of large-scale reduction in down wood are not presently well understood. In ponderosa pine associations, down wood is sparse because of periodic surface fires (Hall, 1976). In contrast, down wood is abundant in grand fir, subalpine fir, and western larch associations because of the long interval between stand-replacement fires. Down wood comprises 38% of the foraging substrate used by pileated woodpeckers (*Dryocopus pileatus*) (Bull and Holthausen, 1993). The main food items are carpenter ants (*Camponotus* spp.) and thatching ants (*Formica* spp.) in the Blue Mountains (Bull et al., 1992). Northern flickers (*Colaptes auratus*) and black-backed woodpeckers (*Picoides arcticus*) also forage on down logs. A high percentage of the diet of black bears (*Ursus americanus*) during the summer and fall consists of ants found in down wood (E.L. Bull, data on file).

The ants that inhabit logs are a primary food source for pileated woodpeckers also serve an important role in forest health. Ants are predators of the western spruce budworm, one of the most important forest-defoliating insects in the Pacific Northwest (Torgersen et al., 1990). Inadequate amounts and kinds of down wood could affect the beneficial role that foliage-foraging ants and other forest-floor arthropods have in maintaining forest health (Torgersen and Bull, 1995). Fellin (1980) found that populations of all forest-floor arthropods were significantly lower on areas that had been harvested and burned compared to adjacent undisturbed forests three years after treatment. Thus, prescribed burning of residues severely affects many groups of forest-floor fauna by directly killing the organisms and by removing woody material and forest floor that are required by these insects for food and shelter (Fellin, 1980). Many species of forest-floor arthropods are predators of the western spruce budworm and some species of budworm parasites depend on the forest floor for a portion of their life cycle.

Down wood also provides cover for small mammals, rubber boas (*Charina bottae*), long-toed salamanders (*Ambystoma macrodactylum*), black bears, American martens (*Martes americana*), and others. American martens use hollow logs for denning and shelter in mixed conifer stands. Black bears use hollow grand fir and western larch logs for hibernation. Heavy accumulations of ‘jackstrawed’ down logs are critical to martens in the winter because they provide spaces under the snow where martens rest and hunt in the Blue Mountains (E.L. Bull, unpublished data). These under-snow areas are also used extensively by red squirrels (*Tamiasciurus hudsonicus*), which are a primary prey item of martens in the winter.

Of the amphibians and reptiles that live in forests of the Blue Mountains, the rubber boa may be the most vulnerable to fire because it spends much of the time hiding under fallen logs or other debris on the ground (Mushinsky, 1994). The rubber boa may require special consideration to ensure that its survival is not threatened by prescribed burning (Mushinsky, 1994).

Although most logs used for foraging, denning, and hibernating are large in diameter, small-diameter logs also have value in providing cover for a variety of small mammals. After a prescribed burn in subalpine fir in central Washington, populations of Townsend’s chipmunks (*Tamias townsendii*), Douglas squirrels (*Tamiasciurus douglasii*), and red-backed voles (*Clethrionymus gapperi*) decreased, and populations of the yellow pine chipmunk (*Tamias amoenus*) remained the same or increased slightly (Hanson, 1978). Deer mice (*Peromyscus maniculatus*) are a pioneer species and may increase after burning (Ream, 1981).

The reduction in small mammals after a prescribed fire will also affect those species that prey on small mammals, notably carnivores and raptors. The importance of down wood to prey of the great gray owl is demonstrated by the occurrence of a log within 1 m of 77% of the attempted prey captures by radio-tagged adult owls (Bull et al., 1988).

Season of burning can influence wildlife, as well as other resources (Wisdom and Thomas, 1996). A spring burn can eliminate reproduction in ground-nesting birds. A fall burn may increase soil erosion by wind and water, eliminate plant biomass that could hold snow and provide moisture during snow melt, could increase frost damage to understory plants, and eliminate forage for elk during the initial winter after burning (Jourdonnais and Bedunah, 1990).

Research is needed to determine how much and what kind of down wood can be removed without jeopardizing wildlife populations (Hagan and Grove, 1999). In addition, research needs to evaluate the effect charring has on the thermoregulatory characteristics of logs to determine if they have the same wildlife value as uncharred logs. Large-diameter logs, which have the greatest value to wildlife, are less likely to burn completely and can be protected more easily than smaller logs. Removing combustible materials from the proximity of logs in preparation for a prescribed burn may help protect these logs, but it is expensive and rarely done in the Blue Mountains.

7.2. Snags

Snags are both lost and created during most prescribed burns; the extent of each change depends on the intensity of the fire and the precautionary measures taken to protect snags and green trees. Typically, the snags created are small in diameter and are the understory growth that some prescribed burning is designed to eliminate. These newly created small-diameter snags provide foraging opportunities for woodpeckers for several years, but are typically too small for nesting cavities. Creating snags and the subsequent influx of woodpeckers contributed to an increase in bird diversity after prescribed burning, even though bird densities did not change in central Washington (Hanson, 1978).

The loss of existing cavity trees of the endangered red-cockaded woodpecker (*Picoides borealis*) has been reported in prescribed burning in longleaf pine in east Texas (Conner, 1979). Conner recommended raking all combustible material away from the bases of cavity trees in at least a 3-m radius to protect the trees.

Existing snags can be protected by removing combustible material from around them, but it is costly and is rarely done before prescribed burning in the Blue Mountains. Nonetheless, this approach is recommended for all snags >30 cm DBH. The loss of snags >30 cm DBH with some decay reduces the number of potential nest trees for both primary and secondary cavity nesters. The loss of nest trees will likely result in lower densities of cavity nesters.

7.3. Species composition and stand structure

The long-term effects of converting stands of mature mixed conifers to stands dominated by ponderosa pine and western larch will be less obvious than the immediate effects of reducing down wood and snags. The converted stands, probably, will be more open and contain less diversity in tree species and structure.

How these conversions affect deer and elk will depend on whether forage or cover is more limiting in the area. In the Blue Mountains, cover is typically more limiting than forage because of past harvesting practices (Leckenby et al., 1991). Conversion to more open stands will further reduce cover, which is already in short supply.

Wildlife species characteristic of mature stands of ponderosa pine will probably benefit from these stand conversions if the stands are allowed to reach mature age. The draft Columbia River Basin EIS (Wisdom et al., in press) classifies three of these species as focus species or of special concern because of low numbers; they are the white-headed woodpecker (*Picoides albolarvatus*), the pygmy nuthatch (*Sitta pygmaea*), and the white-breasted nuthatch (*S. carolinensis*).

The draft Columbia River Basin EIS (Wisdom et al., in press) identifies 22 focus species characteristic of mature stands of grand fir that will probably not benefit from these stand conversions. Eight of the 22 species of special concern are the pileated woodpecker, Vaux's swift (*Chaetura vauxi*), northern goshawk (*Accipiter gentilis*), northern flying squirrel (*Glaucomys sabrinus*), hoary bat (*Lasiurus cinereus*), silver-haired bat (*Lasionycteris noctivagans*), American marten, and fisher (*Martes pennanti*).

Before large-scale prescribed burning is adopted, a careful evaluation of the potential consequences to wildlife and other management objectives is warranted. Other methods of reducing fuels could produce fewer detrimental consequences and more control. Mechanically removing down wood would reduce the fuels and protect the larger down wood and snags. In the short term, mechanical removal may be more expensive, but may be more economical in the long term if snags and large-diameter logs lost in prescribed burns have to be replaced to provide suitable habitat for those wildlife species that depend on them. Prescribed fires produce a complex array of changes, not just for wildlife, but for nutrient recycling and productivity as well, the consequences of which are poorly understood. Caution, a conservative approach, and alternative methods are warranted until research better defines the consequences of prescribed burning on all resources.

8. Conclusions and recommendations

Solutions for the prevalent forest health problems in the Blue Mountains and other temperate region forests (the Intermountain and Rocky Mountain areas) are not as simple or straightforward as attempting to return those systems to a condition that emulates presettlement conditions. Even if we understood the forest structure at that time, whether returning to it is possible—or even desirable—is questionable, except perhaps on a small scale. Prescribed fire, as a means of achieving stand conversions, should be applied with caution because there are many unknown and poorly predictable dimensions and long-term consequences.

We have attempted to address two aspects of resource management that will undoubtedly be seriously affected by prescribed fire conversion of large areas of forest to seral stands. They are but two of the resource considerations that have become important since the time of European settlement. The futures of forest productivity and wildlife (except as a food resource) were probably not serious considerations then. Nor were air quality, global climate change, biodiversity, threatened and endangered species, water quality, water yield, scenery, soil stability, and erosion. Now, all of these conditions are at the forefront of any plan for forest management.

Federal and State land management agencies must bear their share of responsibility for clean air and for minimizing outputs of atmospheric gases that influence global climate. Prescribed burning may have a double-sided effect. Burning emits CO_x, NO_x, SO_x, and other oxides as well as particulates (Sandberg et al., 1979; Crutzen and Andreae, 1990; Kaufman et al., 1991). If burning lowers forest productivity, the ability of these systems to capture carbon is also reduced, and the effect is a larger net loss of carbon than if losses by burning alone are considered.

Predicting the outcome of succession given any sequence of management strategies in these forest systems will not be easy, and it is complicated by past disturbances (Noble, 1981). We suggest that a more reasonable and realistic approach would be to examine the present condition of forests and assess their potential to provide the full array of resource outputs and values.

Recommendations that fire be the primary tool to achieve and maintain presettlement forest structure is also a matter of concern. Many other management options could be used singly or combined with fire, depending on the objectives for the site. If fire is part of the prescription, intervals between burns should be such as to allow re-establishment of prefire forest floor conditions before reburning. Tiedemann and Klemmedson (1992) raised a key question: How can we manage forest residues and large accumulations of biomass without relying solely on fire? Many, and perhaps most, of the goals of prescribed fire can be reached by mechanically managing residues and the new tree crop. Practical measures that can be implemented as part of harvest include leaving residues in place by lopping and scattering them. Chipping and scattering is an alternative for excessive accumulations of residues, but consequences of that option for soil nutrient availability, succession, and wildlife need to be studied. When fire is selected as the primary tool, longer interval prescribed burning (20–30 years) could reduce the effects on the forest floor, down wood, and, perhaps, productivity.

We also think multi-species and multi-age management of forest stands would be worth consideration, rather than attempting to manage specific seral conditions. Managing for a wider array of tree species and associated understory species would help in solving insect outbreaks and disease epidemics associated with large areas of one or two host-tree species. Wildlife also would likely benefit from this strategy compared to managing for seral species in widely spaced stands.

Until more is known about the effects of prescribed fire on resource productivity and wildlife habitats, a conservative approach seems appropriate. The most prudent course may be a special effort to more fully understand the effects of prescribed fire on forest ecosystems before proceeding with large-scale improvement programs.

Acknowledgements

The authors appreciate the incisive, candid technical reviews by: Ann Camp, Pacific Northwest Research Station, USDA Forest Service; Leo Goebel, Goebel Tree Farms; Fred Hall, Pacific Northwest Region, USDA Forest Service; John Lehmkuhl, Pacific Northwest Research Station, USDA Forest Service; Marvin Hoover, Rocky Mountain Research Station (retired), USDA Forest Service; Mark Huff, Pacific Northwest Region, USDA Forest Service; Jack Lyon, Intermountain Research Station (retired), USDA Forest Service; and Malcolm Zwolinski, School of Renewable Natural Resources, University of Arizona. We also thank the two anonymous reviewers selected by Forest Ecology and Management.

References

Agee, J.K., 1993. Fire and weather disturbances in terrestrial ecosystems of the eastern Cascades. In: Hessburg, P.F. (Compiler), Eastside Forest Ecosystem Health Assessment, vol. III—Assessment. USDA For. Serv., Pac. Northwest Res. Sta. pp. 359–414.

Arthur, M.A., Fahey, T.J., 1990. Mass and nutrient content of decaying boles in an Engelmann spruce–subalpine fir forest, Rocky Mountain National Park. Can. J. For. Res. 20, 730–737.

Baker, W.L., 1992. Effects of settlement and fire suppression on landscape structure. Ecology 73, 1879–1887.

Baldwin, E.M., 1964. Geology of Oregon. University of Oregon Coop. Book Store, Eugene. pp. 165.

Ballard, R., Gessel, S.P. (Technical Eds.), 1983. IUFRO Symposium on Forest Site and Continuous Productivity, Seattle, WA, 22–28 August, 1982, USDA For. Ser., Pac. Northwest For. and Range Exp. Sta., Gen. Tech. Rep. PNW-163. Portland, OR. pp. 406.

Binkley, D., Richter, D., David, M.B., Caldwell, B., 1992. Soil chemistry in a loblolly pine forest with interval burning. Ecol. Appl. 2, 157–164.

Biswell, H.H., 1973. Fire ecology in a ponderosa pine grassland. In: Proceedings, Tall Timbers Fire Ecology Conference. Tall Timbers Res. Sta., Tallahassee, FL. pp. 69–73.

Bonnickson, T.M., Stone, E.C., 1985. Restoring naturalness to national parks. Environ. Manage. 9, 479–486.

Borchers, J.G., Perry, D.A., Sollins, P., Koerper, G., Cromack, Jr., K., 1993. Short-term carbon and nitrogen depletion from forests following clearcutting and prescribed burning in southwest Oregon. Bull. Ecol. Soc. Am. 74 (Supplement 2).

Boyer, W.D., 1987. Volume growth loss: a hidden cost of periodic prescribed burning in longleaf pine? South. J. Appl. For. 11, 154–157.

Brown, J.K., Arno, S.F., 1991. Solving the growing predicament in managing wildland fires. Proc. Soc. Am. Foresters Nat'l Conv., San Francisco, CA. August 4-7, 1991.

Brown, T.H., 1977. Nutrient distributions of two eastern Washington forested sites. Master of Science thesis, Wash. State Univ., Pullman, WA. pp. 111.

Bull, E.L., Henjum, M.G., Rohweder, R.S., 1988. Nesting and foraging habitat of great gray owls. J. Raptor Res. 22, 107–115.

Bull, E.L., Beckwith, R.C., Holthausen, R.S., 1992. Arthropod diet of pileated woodpeckers in northeastern Oregon. Northwest. Naturalist 73, 42–45.

Bull, E.L., Holthausen, R.S., 1993. Habitat use and management of pileated woodpeckers in northeastern Oregon. J. Wildl. Manage. 57, 335–345.

Busse, M.D., 1994. Downed bole-wood decomposition in lodgepole pine forests of central Oregon. Soil Sci. Soc. Am. J. 58, 221–227.

Campbell, C.A., 1978. Soil organic carbon, nitrogen and fertility. In: Schnitzer, M., Khan, S.U. (Eds.), Soil Organic Matter, Elsevier, Amsterdam. pp. 173–271.

Caraher, D.L., Henshaw, J., Hall, F.C., Knapp, W.H., McCammon, B.P., Nesbitt, J., Pedersen, R.J., Regenovitch, F., Tietz, C., 1992. Restoring ecosystems in the Blue Mountains. USDA For. Serv., Pac. Northwest Reg., Portland, OR. pp. 14.

Cochran, P.H., Hopkins, W.E., 1991. Does fire exclusion increase productivity of ponderosa pine? In: Harvey, A.E., Neuenschwander, L.F. (Compilers), Proc., Management and Productivity of Western-Montane Forest Soils. USDA For. Serv. Gen. Tech. Rep. INT-280. pp. 224–228.

Conner, R.N., 1979. Effects of a prescribed burn on cavity trees of red-cockaded woodpeckers. Wildl. Soc. Bull. 7, 291–293.

Cooper, C.F., 1960. Changes in vegetation, structure, and growth of southwestern ponderosa pine forests since white settlement. Ecol. Monogr. 30, 129–164.

Covington, W.W., Sackett, S.S., 1984. The effect of a prescribed burn in southwestern ponderosa pine on organic matter and nutrients in woody debris and forest floor. For. Sci. 30, 183–192.

Covington, W.W., Sackett, S.S., 1986. Effect of periodic burning on soil nitrogen concentration in ponderosa pine. Soil Sci. Soc. Am. J. 50, 452–457.

Covington, W.W., Sackett, S.S., 1990. Fire effects on ponderosa pine soils and their management implications. In: Effects of Fire Management of Southwestern Natural Resources. USDA For. Serv. Gen. Tech. Rep. RM-191. pp. 105–111.

Covington, W.W., Sackett, S.S., 1992. Soil mineral nitrogen changes following prescribed burning in ponderosa pine. For. Ecol. Manage. 54, 175–191.

Covington, W.W., Moore, M.M., 1994. Southwestern ponderosa forest structure: changes since Euro-American settlement. J. For. 58, 39–47.

Covington, W.W., Fule, P.Z., Moore, M.M., Hart, S.C., Kolb, T.E., Mast, J.N., Sackett, S.S., Wagner, M.R., 1997. Restoring ecosystem health in ponderosa pine forests of the southwest. J. For. 95(4), 23–29.

Crutzen, P.J., Andreae, M.O., 1990. Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. Science 250, 1669–1678.

DeBano, L.F., 1991. The effects of fire on soil properties. In: Harvey, A.E., Neuenschwander, L.F. (Compilers), Proceedings, Management and Productivity of Western-Montane Forest Soils. Boise, ID, 10–12 April, 1990. USDA For. Serv. Gen. Tech. Rep. INT-280. Intermountain Res. Sta., Ogden, UT. pp. 151–156.

DeBano, L.F., Conrad, C.W., 1978. Effects of fire on nutrients in a chaparral ecosystem. Ecology 59, 489–497.

DeBano, L.F., Neary, D.G., Ffolliott, P.F., 1998. Fire's Effects on Ecosystems, John Wiley & Sons, New York, pp. 333.

Edmonds, R.L., 1979. Decomposition and nutrient release in Douglas-fir needle litter in relation to stand development. Can. J. For. Res. 9, 132–140.

Everett, R.L., Hessburg, P.F., Jensen, M.E., Bormann, B.T., 1993. Eastside Forest Ecosystem Health Assessment. vol. 1, Executive Summary. USDA, National For. Syst. and For. Serv. Res., Portland, OR. pp. 57.

Fellin, D.G., 1980. Effects of silvicultural practices, residue utilization, and prescribed fire on some forest floor arthropods. In: Symposium Proc., Environmental Consequences of Timber Harvesting in Rocky Mountain Coniferous Forests. USDA For. Serv. Gen. Tech. Rep. INT-90., Ogden, UT. pp. 287–316.

Fowler, W.B., Helvey, J.D., Johnson, C., 1979. Baseline climatic and hydrologic relationships for the High Ridge Evaluation Area. USDA For. Serv. Gen. Tech Rep. PNW-91, Portland, OR. pp. 17.

Freedman, B., 1981. Intensive forest harvest: a review of nutrient budget considerations. Information Report M-X-121. Maritime For. Res. Cen., Can. For. Serv., Fredericton, N.B. pp. 77.

Fritts, H.C., Lofgren, G.R., Gordon, G.A., 1979. Variations in climate since 1602 as reconstructed from tree rings. Quaternary Res. 12, 18–46.

Gast, W.R. Jr., Scott, D.W., Schmitt, C., Clemens, D., Howes, S., Johnson, C.G. Jr., Masm, R., Mohr, F., Clapp, R.A., 1991. Blue Mountains forest health report. Summary and recommendations: 'New Perspectives in Forest Health'. USDA For. Serv., Pac. Northwest Reg., Portland, OR. 30 p.

Geist, J.M., Strickler, G.S., 1978. Physical and chemical properties of some Blue Mountain soils in northeast Oregon. USDA For. Serv. Res. Pap. PNW-236, Portland, OR. pp. 19.

Geist, J.M., Cochran, P.H., 1991. Influences of volcanic ash and pumice deposition on productivity of western interior forest soils. In: Harvey, A.E., Neuenschwander, L.F. (Compilers), Proc., Management and Productivity of Western-Montane Forest Soils. USDA For. Serv. Gen. Tech. Rep. INT-280, Ogden, UT. pp. 82–88.

Grier, C.G., Lee, K.M., Nadkarni, N.M., Klock, G.O., Edgerton, P.J., 1989. Productivity of forests in the United States and its relation to soil and site factors and management practices: a review. USDA For. Serv. Gen. Tech. Rep. PNW-222, Portland, OR. pp. 51.

Hagan, J.M., Grove, S.L., 1999. Coarse woody debris. J. Forestry, January: 6–11.

Hall, F.C., 1973. Plant communities of the Blue Mountains in eastern Oregon and southwestern Washington. USDA For. Serv. Pac. Northwest Region, R-6 Area Guide 3-2. pp. 51.

Hall, F.C., 1976. Fire and vegetation in the Blue Mountains: implications for land managers. Tall Timbers Fire Ecol. Conf., 15. pp. 155–170.

Hamilton, Jr., D.A., Wykoff, W.R., 1988. Impact of species composition on site productivity in the northern Rocky Mountains. In: Schmidt, W.C. (Compiler), Proceedings—Future Forests of the Mountain West: A Stand Culture Symposium, USDA For. Serv. Gen. Tech. Rep. INT-243, Ogden, UT. pp. 240–248.

Hanson, E.E., 1978. The impact of a prescribed burn in a temperate subalpine forest upon the breeding bird and small mammal populations. MS Thesis. Cent. Wash. University, Ellensburg, WA. pp. 56.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gegory, S.V., Lattin, J.O., Anderson, N.H., Cline, J.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, H. Jr., Cummins, K.W., 1986. Ecology of course woody debris in temperate ecosystems. In: MacFadyen, A., Boyd, E.D. (Eds.), Advances in Ecological Research. Academic Press, London. pp. 133–302.

Harvey, A.E., Jurgensen, M.F., Larsen, M.J., 1976. Intensive fiber utilization and prescribed fire: effects on the microbial ecology of forests. USDA For. Serv. Gen. Tech. Rep. INT-28, Ogden, Ut. pp. 46.

Hessburg, P.F., Mitchell, R.G., Filip, G.M., 1994. Historical and current roles of insects and pathogens in eastern Oregon and Washington forested landscapes. USDA For. Serv. Gen. Tech. Rep. PNW-GTR-327, Portland, OR. pp. 72.

Heyerdahl, E.K. 1997. Spatial and temporal variation in historical fire regimes of the Blue Mountains, Oregon and Washington: the influence of climate. Ph.D. Dissertation, University of Washington. pp. 224.

Hoover, M.D., Lunt, H.A., 1952. A key for the classification of forest humus types. Soil Sci. Soc. Am. Proc. 16, 368–370.

Hulbert, L.C., 1969. Fire and litter effects in undisturbed bluestem. Ecology 50, 874–877.

Jenny, H., Gessel, S.P., Bingham, F.T., 1949. Comparative study of decomposition rates of organic matter in temperate and tropical regions. Soil Sci. 68, 419–432.

Johnson, Jr., C.G., Clausnitzer, R.R., 1992. Plant associations of the Blue and Ochoco mountains. USDA For. Serv. R6-ERW-TP-036-92, Portland, OR. pp. 164.

Johnson, H.B., Mayeux, H.S., 1992. Viewpoint: a view on species additions and deletions and the balance of nature. J. Range Manage. 45, 322–333.

Jourdonnais, C.S., Bedunah, D.J., 1990. Prescribed fire and cattle grazing on an elk winter range in Montana. Wildl. Soc. Bull. 18, 232–240.

Jurgensen, M.F., Harvey, A.E., Graham, R.T., Page-Dumroese, D.S., Tonn, J.R., Larsen, M.J., Jain, T.B., 1997. Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of inland northwest forests. For. Sci. 43, 234–251.

Kaufman, Y.J., Fraser, R.S., Mahoney, R.L., 1991. Fossil fuel and biomass burning effect on climate–heating or cooling? J. Climate 4, 578–588.

Keane, R.E., Arno, S.F., Brown, J.K., 1990. Simulating cumulative fire effects in ponderosa pine/Douglas-fir forests. Ecology 71, 189–203.

Kimmins, J.P., 1977. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. For. Ecol. Manage. 1, 169–183.

Kittredge, J., 1948. Forest Influences, McGraw–Hill, New York. pp. 394.

Klemmedson, J.O., 1975. Nitrogen and carbon regimes in an ecosystem of young dense ponderosa pine. For. Sci. 21, 163–168.

Klemmedson, J.O., 1976. Effect of thinning and slash burning on nitrogen and carbon in ecosystems of young, dense ponderosa pine. For. Sci. 22, 45–53.

Klemmedson, J.O., Schultz, A.M., Jenny, H., Biswell, H.H., 1962. Effect of prescribed burning of forest litter on total soil nitrogen. Soil Sci. Soc. Am. Proc. 26, 200–202.

Klemmedson, J.O., Tiedemann, A.R., 1995. Effects of nutrient stress. In: Bedunah, D.J., Sosebee, R.E. (Eds.), Wildland Plants—Physiological Ecology and Developmental Morphology. Soc. Range Manage., Denver, CO. pp. 414–439.

Koelling, M.R., Kucera, C.L., 1965. Dry matter losses and mineral leaching in bluestem standing crop and litter. Ecology 46, 529–532.

Kovacic, D.A., Swift, D.M., Ellis, J.E., Hakonson, T.E., 1986. Immediate effects of prescribed burning on mineral soil nitrogen in ponderosa pine in New Mexico. Soil Sci. 41, 71–76.

Landsberg, J.D., 1992. Response of ponderosa pine forests in central Oregon to prescribed underburning. Ph.D. Diss., Ore. State University, Corvallis, OR. pp. 282.

Landsberg, J.D., 1994. A review of prescribed fire and tree growth response in the genus *Pinus*. In: Proceedings, 12th Conf. on Fire and Forest Meteorology, Soc. Am. For. pp. 326–346.

Laycock, W.A., 1991. Stable states and thresholds of range condition on North American rangelands: a viewpoint. J. Range Manage. 44, 427–433.

Leckenby, D., Wheaton, C., Bright, L., 1991. Elk vulnerability—the Oregon situation. In: Christensen, A.G., Lyon, L.J., Lonner, T.N. (Compilers), Proceedings of elk vulnerability—a symposium. Mont. State Univ., Bozeman, MT. pp. 89.

Little, S.N., Ohmann, J.L., 1988. Estimating nitrogen lost from forest floor during prescribed fires in Douglas-fir/western hemlock clearcuts. For. Sci. 34, 152–164.

Major, J., 1974. Biomass accumulation in successions (Chap. 19) and Nitrogen accumulation in successions (Chap. 20). In: Knapp, R. (Ed.), Handbook of Vegetation Science, Part VIII. Vegetation Dynamics. Dr. W. Junk b.v.-Publishers, The Hague. pp. 197–213.

Malkonen, E., 1975. Whole tree utilization—consequences for soil and environment. In: Whole-Tree Utilization—Consequences for Soil and Environment. Konferens SK2, Elmia 75, Jonkoping, Sweden. pp. 26–30.

Maser, C., Trappe, J.M., 1984. The seen and unseen world of the fallen tree. USDA For. Serv. Gen. Tech. Rep. PNW-164, Portland, OR. pp. 56.

Mason, R.R., Wickman, B.E., 1988. The Douglas-fir tussock moth in the interior Pacific Northwest. In: Berryman, A.A. (Ed.), Dynamics of Forest Insect Populations, Chap. 10. Plenum Press, New York.

McNabb, D.H., Cromack, Jr., K., 1990. Effects of prescribed fire on nutrients and soil productivity. In: Walstad, J.D., Radosevich, S.R., Sandberg, D.V. (Eds.), Natural and Prescribed Fire in Pacific Northwest Forests. Corvallis, Oregon. Oregon State University Press. pp. 125–142.

Monleon, V.J., Cromack Jr., K., Landsberg, J.D., 1997. Short- and long-term effects of prescribed underburning on nitrogen availability in ponderosa pine stands in central Oregon. Can. J. For. Res. 27, 369–378.

Mushinsky, H.R., 1994. The effects of fire on amphibians and reptiles. Nat. Res. News, March 1994. Blue Mountains Nat. Res. Inst., LaGrande, OR. pp. 4–6, 8.

Mutch, R.W., Arno, S.F., Brown, J.K., Carlson, C.E., Ottmar, R., Peterson, J.L., 1993. Forest health in the Blue Mountains: a management strategy for fire-adapted ecosystems. In: Quigley, T.M. (Ed.) Forest Health in the Blue Mountains: Science Perspectives. USDA For. Serv. Gen. Tech. Rep. PNW-GTR-310, Portland, OR. pp. 14.

National Oceanic and Atmospheric Administration, 1984. Climatological data, annual summary, Oregon, 1984. vol. 90, No. 13. National Climatic Data Center, Asheville, NC. pp. 34.

Noble, I.R., 1981. Predicting successional change. In: Mooney, H.A., Bonnicksen, T.M., Christensen, N.L., Lotan, J.E., Reiners, W.A. (Eds.). Fire Regimes and Ecosystem Properties, Proceedings of a Conference. USDA For. Serv. Gen. Tech. Rep. WO-26, Washington, DC. pp. 278–300.

Odum, E.P., 1969. The strategy of ecosystem development. Science 164(3877), 262–270.

Ojima, D.S., Parton, W.J., Schimel, D.S., Ownsby, C.E., 1988. Simulating the long-term impact of burning on C, N, and P cycling in a tallgrass prairie. In: Giovannozzi-Sermanni G., Nannipieri, P. (Eds.), Current Perspectives in Environmental Biogeochemistry. C.N.R.–I.P.R.A., Via Nizza, 128-00198 Rome. pp. 353–370.

Ojima, D.S., Schimel, D.S., Schimel, W.J., Ownsby, C.E., 1994. Long- and short-term effects of fire on nitrogen cycling in tallgass prairie. Biogeochem. 24, 67–84.

Oliver, W.W., Edminster, C.E., 1988. Growth of ponderosa pine thinned to different stocking levels in the western United States. In: Schmidt, W.C. (Compiler), Proceedings—Future Forests of the Mountain West: A Stand Culture Symposium. USDA For. Serv. Gen. Tech. Rep. INT-243. Ogden, UT. pp. 153–159.

Oliver, W.W., Ryker, R.A., 1990. *Pinus ponderosa* Dougl. ex Laws. Ponderosa Pine. In: Burns, R.M., Honkala, B.H. (Technical Coordinators), Silvics of North America. Vol. 1, Conifers. U.S. Department of Agriculture, Forest Service, Agric. Handbook. 654. Washington, DC. pp. 413–424.

Olson, J.S., 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecology 44, 322–331.

Page-Dumroese, D., Harvey, A., Jurgensen, M., Graham, R., 1991. Organic matter function in the western-montane forest soil system. In: A.E. Harvey, and L.F. Neuenschwander (Compilers), Proceedings—Management and Productivity of Western-Montane Forest Soils. USDA For. Serv. Gen. Tech. Rep. INT-280. Ogden, UT. pp. 95–100.

Paul, E.A., 1970. Characterization and turnover rate of soil humic constituents. In: Pawluk, S. (Ed.), Pedology and Quaternary Research. Univ. of Alberta Press, Alberta, Sask., Can. pp. 63–76.

Powers, R.R., 1991. Are we maintaining the productivity of forest lands? Establishing guidelines through a network of long-term studies. In: Harvey, A.E., Neuenschwande, L.F. (Eds.), (Compilers), Proceedings—Management and Productivity of Western-Montane Forest Soils. USDA For. Serv. Gen. Tech. Rep. INT-280. Ogden, UT. pp. 70–81.

Raison, R.J., 1979. Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: a review. Plant Soil 51, 73–108.

Raison, R.J., Khanna, P.K., Woods, P.V., 1984. Mechanisms of element transfer to the atmosphere during vegetation fires. Can. J. For. Res. 15, 132–140.

Ream, C.H., 1981. The effects of fire and other disturbances on small mammals and their predators: an annotated bibliography. USDA For. Serv. Gen. Tech. Rep. INT-106. Ogden, UT. pp. 55.

Richards, B., 1992. Burning Questions. Wall St. J., 6 October, 1992.

Riegel, G.M., Miller, R.F., Krueger, W.C., 1991. Understory vegetation response to increasing water and nitrogen levels in a *Pinus ponderosa* forest in northeastern Oregon. Northwest. Sci. 65, 10–15.

Rodin, L.E., Bazilevich, N.I., 1967. Production and Mineral Cycling in Terrestrial Vegetation. Oliver and Boyd, London. pp. 288 (translation from Russian).

Sackett, S.S., Hasse, S., Harrington, M.G., 1993. Restoration of southwestern ponderosa pine ecosystems with fire. In: Covington, W.W., DeBano, L.F. (Eds.), Sustainable Ecological Systems: Implementing an Ecological Approach to Land Management. USDA For. Serv. Gen. Tech. Rep. RM-247, Fort Collins, CO. pp. 115–121.

Sandberg, D.V., Pierovich, J.M., Fox, D.G., Ross, E.W., 1979. Effects of fire on air: a state of knowledge review. USDA For. Serv. Gen. Tech. Rep. WO-9. U.S. Government Print. Off., Washington, DC. pp. 40.

Schmidt, W.C., Shearer, R.C., 1990. *Larix occidentalis* Nutt. Western Larch. In: Burns, R.M., Honkala, B.H. (Technical Coordinators), Silvics of North America, vol. 1, Conifers. U.S. Department of Agriculture, Forest Service, Agric. Handbook. 654. Washington, DC. pp. 160–172.

Shea, R.W., 1993. Effects of prescribed fire and silvicultural activities on fuel mass and nitrogen redistribution in *Pinus ponderosa* ecosystems of central Oregon. MS thesis, Oreg. State Univ. Corvallis, OR. pp. 163.

Show, S.B., Kotok, E.I., 1924. The role of fire in the California pine forests. USDA Bull. 1294, Washington, DC. pp. 80.

Soil Survey Division Staff, 1993. Soil Survey Manual. USDA Handbook No. 18, U.S. Gov. Print. Off. Washington, DC. pp. 437.

Stage, A.R., 1973. Prognosis model for stand development. U.S. Department of Agriculture, Forest Service, Res. Pap. INT-137. Intermountain Forest and Range Exp. Sta., Ogden, UT. pp. 32.

Stark, N.M., 1977. Fire and nutrient cycling in a Douglas-fir/larch forest. Ecology 58, 16–30.

Stoszek, K.J., 1978. Management practices and tussock moth hazard. In: Brookes, M.H., Stark, R.W., Campbell R.W. (Eds.), The Douglas-fir Tussock Moth: A Synthesis. USDA For. Serv. Sci. and Education Agency Tech. Bull. 1585. Washington, DC. pp. 188–189.

Swetnam, T.W., Wickman, B.E., Paul, H.G., Baisan, C.H., 1995. Historical patterns of western spruce budworm and Douglas-fir tussock moth outbreaks in the northern Blue Mountains, Oregon, since A.D. 1700. USDA For. Serv. Res. Pap. PNW-RP-484. Portland, OR. pp. 27.

Swift, L.W., Elliott, K.J., Ottmar, R.D., Vihnanek, R.E., 1993. Site preparation burning to improve southern Appalachian pine–hardwood stands: fire characteristics and soil erosion, moisture, and temperature. Can. J. For. Res. 23, 2242–2254.

Swift, M.J., Heal, O.W., Anderson, J.M., 1979. Decomposition in Terrestrial Ecosystems. University of California Press, Berkeley, CA. pp. 372.

Tausch, R.J., Wigand, P.E., Burkhardt, J.W., 1993. Viewpoint: plant community thresholds, multiple stable states, and multiple successional pathways: legacy of the Quaternary? J. Range Manage. 46, 439–447.

Tiedemann, A.R., 1981. Stream chemistry, nutrient economy, and site productivity consequences of wildland management and wildfire. In: Baumgartner, D.M. (Ed.), Interior West Watershed Management. Proceedings of a Symposium. Cooperative Extension, Washington State University, Pullman, WA. pp. 183–201.

Tiedemann, A.R., 1987. Combustion losses of sulfur from forest foliage and litter. For. Sci. 33, 216–223.

Tiedemann, A.R., Klock, G.O., 1977. Meeks Table Research Natural Area: reference sampling and habitat classification. USDA For. Serv. Res. Pap. PNW-223. Portland, OR. pp. 19.

Tiedemann, A.R., Klemmedson, J.O., 1992. Potential impacts of prescribed burning on sustainable forest productivity. Natural Resource News 2(2): 9. Blue Mountains Nat. Res. Inst., LaGrande, OR.

Tiedemann, A.R., Mason, R.R., Wickman, B.E., 1998. Forest floor and soil nutrients 5 years after urea fertilization in a grand fir forest. Northwest. Sci. 72, 88–95.

Tiedemann, A.R., Parks, C.A., Muzika, R.M., Mason, R.R., Marx, D.B., Wickman, B.E., Forest floor, soil, understory, and tree responses to 3 fertilizer formulations in mixed conifer forest (in review).

Tiedemann, A.R., Conrad, C.E., Dieterich, J.H., Hornbeck, J.W., Megahan, W.F., Viereck, L.A., Wade, D.D., 1979. Effects of fire on water: a state of knowledge review. USDA For. Serv. Gen. Tech. Rep. WO-10. U.S. Gov. Print. Off. Washington, DC. pp. 28.

Torgersen, T.R., Mason, R.R. and Campbell, R.W., 1990. Predation by birds and ants on two forest insect pests in the Pacific Northwest. In: Morrison, M.L., Ralph, C.J., Verner, J., Jehl, Jr., J.R. (Eds.), Avian Foraging: Theory, Methodology, and Applications. Studies in Avian Biology, No. 13. pp. 14–19.

Torgersen, T.R., Bull, E.L., 1995. Down logs as habitat for forest-dwelling ants—the primary prey of pileated woodpeckers in northeastern Oregon. Northwest. Sci. 69, 294–303.

Vance, E.D., Henderson, G.S., 1984. Soil nitrogen availability following long-term burning in an oak–hickory forest. Soil Sci. Soc. Am. J. 48, 184–189.

Vose, J.M., Swank, W.T., 1993. Site preparation burning to improve southern Appalachian pine–hardwood stands: aboveground biomass, forest floor mass, and nitrogen and carbon pools. Can. J. For. Res. 23, 2255–2262.

Wellner, C.A., 1978. Effects of past events. In: Brookes, M.H., Stark, R.W., Campbell, R.W. (Eds.), The Douglas-fir Tussock Moth: A Synthesis. USDA For. Serv. Sci. and Educ. Agency Tech. Bull. 1585., Washington, DC. pp. 185–188.

Wells, C.G., Campbell, R.E., DeBano, L.F., Lewis, C.E., Fredriksen, R.L., Franklin, E.C., Froelich, R.C., Dunn, P.H., 1979. Effects of fire on soil: a state of knowledge review. USDA For. Serv. Gen. Tech. Rep. WO-7. U.S. Gov. Print. Off., Washington, DC. pp. 34.

White, A.S., 1985. Presettlement regeneration patterns in a southwestern ponderosa pine stand. Ecology 66, 589–594.

Wickman, B.E., 1992. Forest health in the Blue Mountains: the influence of insects and diseases. In: Quigley T.M. (Ed.), Forest Health in the Blue Mountains: Science Perspectives. USDA For. Serv. Gen. Tech. Rep. PNW-GTR-295. Portland, OR. pp. 14.

Wienhold, B.J., Klemmedson, J.O., 1992. Effect of prescribed fire on nitrogen and phosphorus in Arizona chaparral soil–plant systems. Arid Soil Res. Rehab. 6, 285–296.

Wisdom, M.J., Thomas, J.W., 1996. Elk. In: Krausman, P.R. (Ed.), Rangeland Wildlife, Soc. Range Manage., Denver, CO. pp. 157–181.

Wisdom, M.J., Holthausen, R.S., Wales, B.C., in press. Source habitats for terrestrial vertebrates of focus in the Interior Columbia Basin: broad-scale trends and management implications. Gen. Tech. Rep. PNW-GTR-XXX. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Woodmansee, R.G., Wallach, L.S., 1981. Effects of fire regimes on biogeochemical cycles. In: Clark, F.E., Rosswall, T. (Eds.), Terrestrial Nitrogen Cycles. Ecol. Bull. (Stockholm), 33. pp. 649–669.

Woodard, P.M., 1977. Effects of prescribed burning on two different-aged high-elevation plant communities in Eastern Washington, Ph.D. Diss., University of Washington, Seattle, WA. pp. 228.

Woodard, P.M., 1993. Plant survival after a prescribed crown fire in the Cascade Mountains of eastern Washington. In: Proceedings, 12th Conference on Fire and Forest Meteorology, 26–28 October, Jeckyll Island, GA. pp. 729–735.

Wright, R.J., Hart, S.C., 1997. Nitrogen and phosphorus status in a ponderosa pine forest after 20 years of interval burning. Ecosci. 4, 526–533.