Root Diseases in Coniferous Forests of the Inland West: Potential Implications of Fuels Treatments

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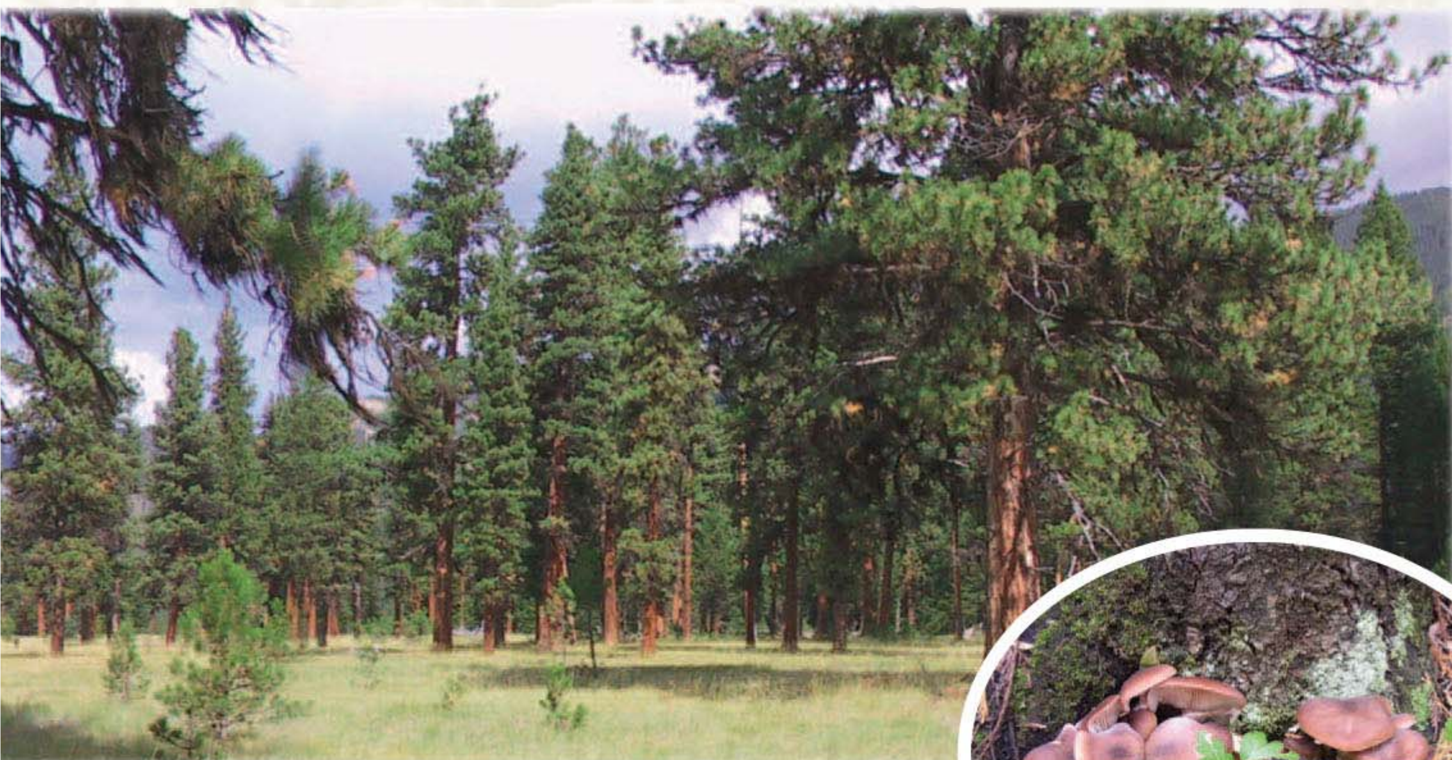

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Abstract

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After nearly 100 years of fire exclusion, introduced pests, and selective harvesting, a change in forest composition has occurred in many Inland West forests of North America. This change in forest structure has frequently been accompanied by increases in root diseases and/or an unprecedented buildup of fuels. Consequently, many forest managers are implementing plans for fuels treatments to lower the risk of severe wildfires.

Impacts on root disease should be considered before selecting appropriate fuels treatments. Complex interactions exist among conifer root diseases, fuels treatments, forest structure, species composition, stand history, and other environmental factors. As forest managers prescribe fuels treatments, their success in lowering the risk of severe wildfire will depend in part on the impacts of these treatments on root disease. Root diseases are one of many factors to be considered when developing plans for fuels treatments. Choices must be made on a site-by-site basis, with knowledge of the diseases that are present.

This paper provides examples of how fuels treatments may increase or reduce specific diseases and demonstrates their importance as considerations in the fuels management planning process. Several root diseases prevalent within Inland West of North America are addressed: Armillaria root disease, annosus root disease, laminated root rot, black stain root disease, Schweinitzii root and butt rot, Tomentosus root disease, Rhizina root rot, and stringy butt rot. For each disease, general information is provided on disease identification, management options, and potential effects of fuels treatments. However, many long-term studies are needed to assess effects of specific interactions among fuels treatments, root diseases, and host trees.

Key words: wildfire, forest planning, forest structure, mechanical treatments, prescribed fire, coniferous hosts, pathogens, disease management

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Foreword

This document is part of the Fuels Planning: Science Synthesis and Integration Project, a pilot project initiated by the USDA Forest Service to respond to the need for tools and information useful for planning site-specific fuel (vegetation) treatment projects. The information addresses fuel and forest conditions of the dry inland forests of the Western United States: those dominated by ponderosa pine, Douglas-fir, dry grand fir/white fir, and dry lodgepole pine potential vegetation types. Information was developed primarily for application at the stand level and is intended to be useful within this forest type regardless of ownership. Portions of the information also will be directly applicable to the pinyon pine/juniper potential vegetation types. Many of the concepts and tools developed by the project may be useful for planning fuel projects in other forests types. In particular, many of the social science findings would have direct applicability to fuel planning activities for forests throughout the United States. As is the case in the use of all models and information developed for specific purposes, our tools should be used with a full understanding of their limitations and applicability.

The science team, although organized functionally, worked hard at integrating the approaches, analyses, and tools. It is the collective effort of the team members that provides the depth and understanding of the work. The science team leadership included the following USDA Forest Service personnel:

- Deputy Science Team Leader Sarah McCaffrey, North Central Research Station
- Forest structure and fire behavior: Dave Peterson and Morris Johnson, Pacific Northwest Research Station
- Environmental consequences: Elaine Kennedy-Sutherland and Anne Black, Rocky Mountain Research Station
- Economic uses of materials: Jamie Barbour and Roger Fight, Pacific Northwest Research Station
- Public attitudes and beliefs: Pamela Jakes and Susan Barro, North Central Research Station
- Technology transfer: John Szymoniak, Pacific Southwest Research Station

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RMRS

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Contents

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Introduction

The effects of nearly 100 years of fire exclusion, introduced pests, and selective timber harvesting have caused dramatic changes in tree species composition across much of the Western landscape. These changes have contributed to an unprecedented buildup of fuels and increased incidence of root disease (Tiedemann and others 2000). Heavy accumulations of fuels and ample fuel ladders have put stands at risk for uncharacteristically severe wildfires. Consequently, many forest managers are implementing plans for fuels treatments to lower the risk of fire. An understanding of how these fuels treatments might affect the many complex interactions that exist within forest ecosystems is critical because even subtle disturbances can trigger associated responses from many coexisting organisms (Borchers and Perry 1990).

Historically, root diseases have played an important and beneficial role in ecological processes of succession, decomposition, and fire in forests with moderate- to high-intensity fire regimes (Hessburg and others 1994; Hansen and Goheen 2000). As with other tree pathogens, native root pathogens are thought to have coevolved with their hosts and are a natural, and even necessary, part of forest ecosystems. In most situations, native root diseases do not cause irreplaceable loss of entire stands over large areas nor threaten the existence of any host species. However, shifts in stand composition and other natural and human-caused disturbances have frequently resulted in increased damage from root-rot diseases (Edmonds and others 2000). In some situations, the change in root rot dynamics may influence forest growth and succession for centuries. Thus, careful consideration of future root disease impacts is critical before implementing any management activities, including fuels treatments.

Whether specific effects of root diseases are considered to be beneficial or detrimental depends on social values and management objectives for the site. For some sites, impacts by root disease in a stand may be viewed as undesirable because of potential increases in fuels buildup, reduced timber volume, damage to facilities from wind-thrown trees, and potential personal injury. At other sites, with different management objectives, loss of trees as a result of root disease may be acceptable or even desirable because of benefits attributed to disease-created openings, scattered mortality (lower density stand), and increased volume of standing and downed large woody debris. Such disease-associated changes may provide forage for large game animals, habitat for small animals and cavity-nesting birds, sources for specialty forest products, increased diversity in the plant community, and other changes in forest structure that reduce the likelihood of catastrophic wildfire (Thies 1999; Filip 1999; Thies and Goheen 2002).

Fuels treatments range widely in approach and application, but generally involve mechanical treatments and/or prescribed fire (Fitzgerald 2002; Graham and others 2004; Peterson and others 2005). Mechanical treatments, such as thinning, can remove fuels as usable forest products, which can include biomass energy. Other types of treatments may involve cutting trees, reducing the size of fuels, eliminating fuels ladders, and methods that place fuels on the forest floor to accelerate decomposition, such as mowing (Fitzgerald 2002). Prescribed fire is also used to reduce surface fuels and ladder fuels; however, the effects of prescribed fire on resulting stand structure are less predictable than mechanical treatments. As forest managers implement plans for fuels treatments, their success in lowering risk of severe wildfire will depend in part on the impacts of management activities on levels of root disease that contribute to subsequent fuels accumulation. The type of fuels treatment can often be selected to match the overall objectives for a stand, while addressing root rot dynamics and possible detrimental effects on a site.

Fuels management practices can influence root disease in complex ways that should be considered at the ecosystem level. Tree thinning can generate stumps and residual root systems that are susceptible to colonization by root-rot pathogens. Stumps, roots, and slash can serve as nutrient substrates that increase the overall growth and distribution of root rot fungi. Thinning-associated wounds on retained trees can provide opportunities for root disease fungi to cause new infections. When seral tree species—for example, pine and larch—are removed in thinning operations, the resulting stand may consist of a higher proportion of tree species that are more susceptible to root rots, such as grand fir or Douglas-fir. Fuels treatments can cause physiological stress to remaining trees, increasing the likelihood that root rot problems will develop. Although the effects of slash burning may vary, superficial burning appears to have little impact on the distribution of pathogens, such as *Armillaria* species, *Phellinus weirii*, or *Heterobasidion annosum*, which frequently occupy protected areas within structural roots (Hadfield and others 1986). However, some measures that limit substrate availability for root pathogens may reduce inoculum and possibly reduce disease severity. Thus, care must be taken to select appropriate fuels treatments that will achieve the objective of reducing current and future fuels levels while avoiding undesirable increases in root disease. Evaluating the presence and distribution of root diseases is an essential step in selecting appropriate fuels treatments. Surveys for root disease include observing signs and symptoms on living trees, and also examining snags, stumps, and overturned trees (Thies 1995).

Although fuels reduction has recently emerged as a national issue, there are few research studies specifically addressing fuels-treatment effects on root diseases. For this reason, much of the information applied to fuels treatments in this paper is based on general principles of plant pathology, knowledge of pathogen biology, and/or derived from studies conducted for other purposes. Because the consequences of root disease resulting from fuels treatments may not be immediately apparent but may continue for decades after treatments, there is an increased need to conduct and interpret long-term studies that examine effects of specific fuels treatment on root disease interactions. Such long-term studies would provide more precise information for understanding these complex relationships.

The objectives of this paper are to (1) provide insights for consideration regarding potential effects of fuels treatments on root diseases, (2) identify specific needs for research pertaining to the effects of fuels treatments on root diseases, and (3) aid field personnel in identification of the primary root diseases. This discussion focuses on the dry, mixed conifer forests between the crest of the Cascade Mountains and the crest of the Rocky Mountains in North America, hereafter referred to as the Inland West. In forests of the Inland West, special attention is warranted for several root diseases, such as Armillaria root rot (caused by *Armillaria* species), Annosus root rot (caused by *Heterobasidion* species), laminated root rot (caused by *Phellinus weirii*), black stain root disease (caused by *Leptographium wageneri*), and Schweinitzii root rot (caused by *Phaeolus schweinitzii*), and other diseases including Tomentosus root disease (caused by *Inonotus tomentosus*), Rhizina root rot (caused by *Rhizina undulata*), and stringy butt rot (caused by *Perenniporia subacida*). Rudimentary information is provided in this paper for identification of these diseases; however, more detailed and definitive field guides with a greater representation of pathogens are available (Partridge and Miller 1974; Partridge and others 1978; Hadfield and others 1986; Scharpf 1993; Allen and others 1996; Filip 1999; Hagle and others 2003). Figures illustrate signs and symptoms of the more common root diseases. We included factors to be considered in the effects of potential fuels treatments on each root disease and identify gaps in research information. Three tables located on the next 3 pages contain general supporting information: table 1 lists common symptoms and signs of each root disease; table 2 lists common coniferous hosts of each root disease; and table 3 lists common and scientific names of pathogens, trees, and insect species.

Table 1—Symptoms and signs associated with common root diseases of conifers of the Inland West.

Root disease (causal fungus)	**Symptoms** (the most diagnostic are in bold text)	**Signs** (the most diagnostic are in bold text)
Armillaria root disease (*Armillaria ostoyae*)	Reduced tree growth Crown thinning and yellowing Smaller, stress cones **Resinosis** (sap on butt/roots) Wood decay/rot: spongy, yellow, stringy	**Mycelial fans within tightly attached bark** Rhizomorphs Fruiting bodies: Honey mushrooms in late summer or fall
Annosus root disease (*Heterobasidion annosum*)	Reduced tree growth Reduced growth of lateral branches Crown thinning and yellowing Smaller, stress cones **Red staining** in the heartwood Wood decay: Spongy, stringy, white with black flecks **Laminated decay**	**Ectotrophic mycelium on roots** Fruiting bodies: Perennial conks: dark brown (top) cream colored, porous (below) First-year conks buff-colored when immature
Black stain root disease (*Leptographium wageneri*)	Reduced tree growth Crown thinning Stress cones **Rapid crown wilting**	**Dark purple-to-black hyphae:** **Stain in recent sapwood and cambium** **Lengthwise stain in lower bole**
Laminated root rot (*Phellinus weirii*)	Reduced tree growth Crown thinning and yellowing Laminated decay in roots/lower bole **Layers of decay contain small pits** Red-brown staining	Ectotrophic mycelium **Reddish-brown setal hyphae** between layers of decayed wood **Fruiting bodies:** flat, cream-brown
Rhizina root disease (*Rhizina undulata*)	**Only in recently burned area** Dead seedlings Sparse foliage Discolored needles Stem resinosis	**Masses of white to yellow mycelia form mats around roots** Fruiting bodies: **Disklike, with multiple rootlike structures scattered across underside** Groups form along or over infected roots Brown to black with age
Schweinitzii root and butt rot (Red-brown butt rot) (*Phaeolus schweinitzii*)	Reduced tree growth Crown thinning and yellowing Gall-swelling of small roots Pronounced butt swelling Yellow/red-brown staining in heartwood **Wood decay:** **Cubical decay**, reddish-brown, crumbly Carpenter ants often occur within decay	**Fruiting bodies:** On ground: **circular or irregularly lobed** On trees: shelf-like Fresh: **Upper surface velvety**, usually reddish-brown with a yellow margin **Older: brown, resembling cow dung**
Stringy butt rot (*Perenniporia subacida*)	Wood decay: **Light brown stain in heartwood** Small white pits in decayed wood, **Masses of stringy, white spongy fibers** with small black flecks Laminated wood decay	**Yellow mycelial mats between layers of decayed wood** Fruiting bodies: On undersides of downed trees and branches of living trees Perennial, flat and leathery to crustlike, cream to light yellow, underside covered in small circular pores
Tomentosus root rot (*Inonotus tomentosus*)	Resin exuded on infected roots Wood decay: **Red stain, small pockets lined with white fibers**	**Fruiting bodies**: Annual, circular, on roots or ground, often united with multiple stems. **Upper surface: velvety**, yellow to brown Lower surface: light brown pores darken when bruised

Table 2—Common coniferous hosts of root diseases of the Inland West. Consult text for major and minor hosts for each pathogen species, form, type, and variety.

	Coniferous hosts			
Root disease	**Pines**	**Douglas-fir and firs**	**Spruce and larch**	**Hemlocks, cedars, juniper, and yew**
Armillaria root disease	Jeffrey pine lodgepole pine ponderosa pine western white pine whitebark pine	Douglas-fir grand fir subalpine fir white fir	Engelmann spruce	juniper mountain hemlock western hemlock western redcedar
Annosus root disease	Jeffrey pine ponderosa pine	Douglas-fir grand fir white fir other true firs	Engelmann spruce	incense cedar juniper mountain hemlock western hemlock
Black stain root disease	Jeffrey pine lodgepole pine pinyon pine ponderosa pine western white pine	Douglas-fir	Can be found on a variety of spruce species, but found only occasionally	Can be found on hemlock species, but found only occasionally
Laminated root rot	Can be found on pines, but not common	Douglas-fir grand fir subalpine fir white fir	Engelmann spruce western larch	mountain hemlock Pacific yew western hemlock
Rhizina root rot	lodgepole pine ponderosa pine western white pine other pine species	Douglas-fir grand fir	Englemann spruce spruce species western larch	western hemlock western redcedar
Schweinitzii root and butt rot	lodgepole pine ponderosa pine western white pine	Douglas-fir true firs	western larch many spruce species	western hemlock western redcedar
Stringy butt rot	lodgepole pine western white pine	Douglas-fir true firs	Engelmann spruce western larch white spruce	western hemlock western redcedar
Tomentosus root rot	lodgepole pine ponderosa pine western white pine	Douglas-fir grand fir white fir	Engelmann spruce white spruce	

Table 3—Common and scientific names for pathogens, tree species, and insect species.

Root diseases	Scientific name of causal fungus
Armillaria root disease	*Armillaria ostoyae*
Annosus root disease	*Heterobasidion annosum*
Black stain root disease	*Leptographium wageneri*
Laminated root rot	*Phellinus weirii*
Rhizina root rot	*Rhizina undulata*
Schweinitzii root and butt root (Red-brown butt rot)	*Phaeolus schweinitzii*
Stringy butt rot (Yellow root rot)	*Perenniporia subacida*
Tomentosus root rot	*Inonotus tomentosus*
Trees	**Scientific name**
Aspens, Cottonwoods	*Populus spp.*
Douglas-fir	*Pseudotsuga menziesii*
Engelmann spruce	*Picea engelmannii*
Grand fir	*Abies grandis*
Incense cedar	*Calocedrus decurrens*
Jeffrey pine	*Pinus jeffreyi*
Juniper	*Juniperus spp.*
Larch	*Larix spp.*
Lodgepole pine	*Pinus contorta*
Mountain hemlock	*Tsuga mertensiana*
Oaks	*Quercus spp.*
Pacific yew	*Taxus brevifolia*
Ponderosa pine	*Pinus ponderosa*
Singleleaf pinyon	*Pinus monophylla*
Spruce	*Picea spp.*
Subalpine fir	*Abies lasiocarpa*
Sugar pine	*Pinus lambertiana*
Western hemlock	*Tsuga heterophylla*
Western larch	*Larix occidentalis*
Western redcedar	*Thuja plicata*
Western white pine	*Pinus monticola*
Whitebark pine	*Pinus albicaulis*
White fir	*Abies concolor*
Insects	**Scientific name**
Douglas-fir beetle	*Dendroctonus pseudotsugae*
Douglas-fir pole beetle	*Pseudohylesinus nebulosus*
Fir engraver beetle	*Scolytus ventralis*
Mountain pine beetle	*Dendroctonus ponderosae*
Western pine beetle	*Dendroctonus brevicomis*

Armillaria Root Disease

Armillaria root disease, also known as shoestring root rot, is caused by a variety of *Armillaria* species that are widely distributed throughout the Western United States, Europe, Asia, Africa, and Australia (Watling and others 1991). In North America, *Armillaria ostoyae* (Romagn.) Herink predominantly infects conifers; whereas other species of *Armillaria* primarily infect hardwoods or are primarily saprophytic (Gregory and others 1991). Ecological roles of *Armillaria* species include those of primary pathogen, secondary invader, and saprophyte. As a primary pathogen, *Armillaria* is capable of killing vigorous hosts, while as a secondary invader it only colonizes hosts predisposed to disease. *Armillaria ostoyae* is the most widespread and aggressive species of *Armillaria* on conifers in forests of the Inland West (Kile and others 1991). It can survive up to several decades in previously infected stumps (Goheen and Otrosina 1998). A recent study estimated that a single pathogenic *A. ostoyae* individual occupied an area of 965 ha (2,385 acres) in a mixed-conifer forest of northeastern Oregon and estimated its age to be between 1,900 and 8,560 years old (Ferguson and others 2003). Thus, Armillaria root disease can be a persistent, long-term influence within forest ecosystems. Armillaria root disease causes significant mortality, wood decay, and growth reduction in infected conifers (Williams and others 1989).

The host range for *A. ostoyae* includes several western conifer species in North America; however, susceptibility of individual tree species may vary depending on site factors and location (Goheen and Otrosina 1998). *Armillaria ostoyae* causes more mortality in forests of the Inland West than in coastal forests (Goheen and Otrosina 1998), but Armillaria root disease is a serious problem in both regions (Morrison 1981; Hadfield and others 1986). Highly susceptible hosts include Douglas-fir, grand fir, and white fir. Other species damaged or killed by *A. ostoyae* include ponderosa pine, Jeffrey pine, lodgepole pine, whitebark pine, western white pine, Engelmann spruce, subalpine fir, western and mountain hemlock, western redcedar, and juniper. Some hardwoods including species of oak, cottonwood, and aspen are damaged or killed by other species of *Armillaria*, such as *A. mellea* (Morrison 1981; Hadfield and others 1986; Filip 1999; Filip and Ganio 2004).

Host range, virulence, and other aspects of the ecological behavior of *Armillaria* species vary with geographic location. It can be difficult to predict where Armillaria root disease might occur (McDonald and others 1987a,b; Kile and others 1991; Mallett and Maynard 1998). On some sites, pines and other species are tolerant to *A. ostoyae*, but on other sites almost all tree species are killed (Goheen and Otrosina 1998). Locations where trees are stressed—such as sites with drainage problems, soil compaction, or those on the outer limits of geographic range for the host—have increased mortality (Close 1988; Gregory and others 1991; Goheen and Otrosina 1998). Occurrence of Armillaria root disease appears to be associated with groups of habitat types called vegetation subseries (McDonald and others 2000). Pathogenic *Armillaria* is rare or absent in hot-dry, cold-dry, and frost-pocket habitat types (McDonald 1998, 1999). Conifers growing on coarse-textured soils are typically at greater risk of developing Armillaria root disease than those growing on fine-textured soils (Mallett and Maynard 1998).

Armillaria root disease is commonly associated with other root diseases, and it may be difficult to tell which disease occurred first or which disease has caused the most damage. Additionally, Armillaria root disease may predispose conifers to bark beetle attacks (Partridge and Miller 1972; Lane and Goheen 1979; Schmitt and others 1984; Schowalter and Filip 1993).

Disease Symptoms and Signs

Most symptoms of Armillaria root disease (reduced height growth, thinning and yellowing of foliage, and/or abundant crops of smaller stress cones) are common to many root diseases. Although not always present, pitch flow just above the ground is a fairly diagnostic symptom on resinous conifer species (fig. 1). Signs that are indicative of Armillaria root disease can be found at the base, roots, and beneath the bark of an infected tree or stump. Signs include:

- Mycelial mats or fans (white, thick, fan-like shapes that can be found under the bark) (fig. 2).
- Rhizomorphs (reddish-black, flat, shoestring-like mycelial cords that are commonly present on or beneath the bark of roots and lower stems and in the soil near infected trees or stumps).
- Presence of honey-colored mushrooms (the fruiting bodies of the pathogen) produced in late summer or fall after rain (fig. 3) (Morrison 1981; Hadfield and others 1986; Williams and others 1989).

Fans and rhizomorphs do not always indicate that mortality has been caused by Armillaria root disease. Pathogenic *Armillaria* is diagnosed if mycelial fans are found within bark that is tightly attached to living wood, especially if resinosis is present at the root crown. Extensive growth of the fungus eventually girdles and kills the tree. As mycelial fans age, they become yellow and begin to disintegrate, but a fan-shaped imprint is left behind in the wood and bark (Goheen and Otrosina 1998). Pitch flow is an indication of the living tree's response to the pathogenic fungus, and the amount of resin flow may be indicative of the amount of *A. ostoyae*-caused colonization in the roots (Omdal and others 2004). In contrast, fans of saprophytic species of *Armillaria* often invade between loosened bark and wood of dead trees or trees dying from other causes. Trees invaded by saprophytic *Armillaria* spp. exhibit little or no evidence of resinosis or wound callus formation (Robinson and others 2004).

As the disease progresses, stands affected by Armillaria root disease display increased mortality, often with uprooted trees with roots broken at some distance from the bole (fig. 4 through 6). Also, as infected trees decay, the cambial tissues and wood

Figure 1—Abundant resin flow at the base and roots of a conifer is a common symptom indicating infection by *Armillaria ostoyae*. (Photo courtesy of R.C. Rippy)

Figure 2—Mycelial fans are present within roots of this grand fir infected with *Armillaria ostoyae*. (Photo courtesy of J.W. Hanna)

Figure 3—Fruiting bodies of *Armillaria* species. *Armillaria ostoyae* commonly fruits in large clusters; however, mushrooms of other *Armillaria* species also grow in clusters. (Photo courtesy of R.C. Rippy)

Figure 4—In this *Armillaria*-caused mortality center, mushrooms from a species of *Armillaria* can be seen in the foreground. (Photo courtesy of J.W. Hanna)

Figure 5—*Armillaria*-caused mortality centers as they appear in mixed conifer stands. (Photos courtesy of J.D. Rogers)

Figure 6—An uprooted ponderosa pine showing decayed roots that have broken at some distance from the bole. These root wad characteristics, with other signs and symptoms, indicate mortality from Armillaria root disease. (Photo courtesy of R.C. Rippy)

become yellowish, moist, stringy, and sometimes have a pungent odor (Goheen and Otrosina 1998). In the later stages of decay, wood becomes spongy, light yellow, and may be marked with numerous black lines, called "zone lines" (Morrison and others 1992). Decayed wood becomes hard and fibrous as it dries, as can be seen in wind-blown trees. Mushrooms produced by *Armillaria* species are often called honey mushrooms because of the honey-colored caps produced by some species (fig. 3). The mushrooms have white spores, gills attached to the stem, minute peg-like hairs at the center of the upper cap, and a cottony ring around the upper stem (stipe). These mushrooms are often found growing in clusters near the bases of infected trees or stumps (fig. 4). Although, mushrooms are typically produced during moist conditions in the late summer and fall, they are sometimes difficult to find, and they are not produced every year. Other species of *Armillaria* produce similar mushrooms, which can make field identification unreliable.

Disease Management

Armillaria root disease is difficult to control because the disease inoculum (mycelium and rhizomorphs that have colonized woody substrates) is nearly impossible to eliminate from a site. In timber-growing areas, management decisions should consider site characteristics (habitat type, soil type, and associated conditions), stand structure, host species composition, stand management history, and *Armillaria* species present to minimize impacts of this disease (Morrison 1981; Hadfield and others 1986; Williams and others 1989; Fox 2000). Impacts of Armillaria root disease can be reduced by:

- Favoring more resistant/tolerant tree species.
- Maintaining tree species diversity.
- Reforesting stands with locally adapted species suitable to the site.
- Promoting tree vigor by minimizing stress and avoiding wounds.
- Reducing inoculum sources through the uprooting of stumps and removal of woody debris (Williams and others 1989; Hagle and Shaw 1991; Roth and others 2000).

These management considerations are especially critical for sites with high levels of inoculum and/or conditions favorable for disease development (Hagle and Shaw 1991). Thinning has also been examined as a possible management option for reducing Armillaria root disease within a stand. Some studies, outside of the Inland West, in the Cascade Range of western Oregon and Washington have shown that precommercial thinning either decreases or does not impact mortality caused by Armillaria root disease (Filip and others 1989; Filip and Ganio 2004). Precommercial thinning may improve tree vigor by decreasing tree stress, thereby reducing infection. In contrast, thinning increased the mortality caused by the disease in several Inland West locations, such as northern Idaho and parts of Canada (Cruickshank and others 1997). Stumps that remain after thinning treatments are a potential inoculum source that could increase new infections (Cruickshank and others 1997). Differences in the results from these studies highlight that site location and plant association can potentially affect outcomes of management choices, and suggest that these factors be considered in planning fuels treatments. More research information about Armillaria root disease has been compiled in Shaw and Kile (1991).

Fuels Treatment Considerations

Because *Armillaria* species can reside deep in the soil and within large woody roots, superficial slash burning or prescribed fire is unlikely to eliminate the pathogen, although these treatments may reduce infection potential indirectly by removing highly susceptible host species that are readily killed by fire (Hadfield and others 1986; Filip and Yang-Erve 1997; Ferguson and others 2003). Mortality caused by *Armillaria* increases fuel loads (Fields 2003). Prescribed fire may be used to reduce fuel loads, which may also reduce inoculum levels above ground by eliminating nutritional substrates for growth of *Armillaria.* However, fire may have minimal direct effects on the pathogen below ground (Filip and Yang-Erve 1997). Yet, fire may have indirect effects on *Armillaria* inoculum by increasing populations of antagonistic soil fungi such as *Trichoderma* (Reaves and others 1990). Studies have demonstrated that *Armillaria* species survive intense fires (Ferguson and others 2003) and can readily colonize roots of trees killed by fire (Blodgett and Lundquist 2004). Fire may increase or decrease the susceptibility of a stand through its influence on species composition, stand structure, and tree vigor. Thinning treatments that favor climax or late-successional host trees will likely aggravate Armillaria root disease. However, thinning that favors early seral species may reduce root disease over the long term. Also, greater spacing can improve tree vigor of seral species, which may increase tolerance to Armillaria root disease.

Recently, a Web-based tool (*Armillaria* Response Tool: *A*RT) has been developed that can estimate risk of Armillaria root disease caused by *A. ostoyae* in dry forests of the Western United States (McDonald and others, in press). This tool uses habitat types to identify sites where *A. ostoyae* may occur, and the tool indicates how some fire reduction activities (fuels management) may exacerbate Armillaria disease within high-risk stands.

Annosus Root Disease

Annosus root disease, caused by *Heterobasidion annosum* (Fr.) Bref., is found in many temperate coniferous forests around the world. It is an endemic pathogen that is common and widely distributed in North America. Although this disease has existed for millennia within coniferous forest ecosystems, harvesting practices have increased its incidence and impacts, especially in Western and Southeastern North America. In many forest stands, annosus root disease has reached epidemic levels (Otrosina and Ferrell 1995).

Within the Inland West, annosus root disease is of most concern on true firs and pines (Schmitt and others 2000). *Heterobasidion annosum* is a genetically diverse organism that is composed of at least three intersterility groups (ISGs), termed S-, P-, and F-types. These groups cannot be distinguished based on appearance, but they differ in pathogenicity and host range and are intersterile (cannot mate) when paired with each other (Goheen and Otrosina 1998; Sullivan and others 2001). Only the S-type (which affects mainly true firs, hemlock, spruce, and Douglas-fir) and the P-type (which affects mostly pines, larch, incense cedar, and juniper) are found in the Inland West (Otrosina and Ferrell 1995; Goheen and Otrosina 1998). Disease-induced mortality of ponderosa pine, in the Inland West, is often observed on dry sites of poor quality (Goheen and Goheen 1989; Lockman 1993). Mortality can also be quite high in natural grand and white fir stands, especially stands that have experienced selective harvesting (Schmitt and others 1984; Chase 1989; Goheen and Goheen 1989). Annosus root disease is often associated with mortality of ponderosa pine or Jeffrey pine in second-generation or partially harvested stands (Schmitt and others 2000). Specificity of the P- and S-types only applies to living hosts; both types will colonize dead wood of almost all coniferous species (Otrosina and Scharpf 1989; Goheen and Otrosina 1998). Because of differences within and among *H. annosum* ISGs and their interaction with host tree species and environmental factors, the behavior of annosus root disease is highly variable (Goheen and Otrosina 1998; Garbelotto and others 1999). Recent research information about annosus root disease has been compiled in Woodward and others (1998).

The fungus spreads primarily in two ways: aerial spread, and local underground tree-to-tree spread (Schmitt and others 2000). Basidiospores released from fruiting bodies of the fungus can travel up to 161 km (100 miles) (Goheen and Otrosina 1998). *Heterobasidion annosum* readily colonizes fresh stumps and stem wounds of all coniferous species except red and yellow cedar (Wallis and Reynolds 1970; Filip and Morrison 1998), and spread from colonized stumps can cause subsequent infections of residual trees via root contacts after thinning operations (Morrison and Johnson 1978; Sullivan and others 2001). Stump surfaces are vulnerable to colonization for up to 4 weeks after harvesting or thinning (Otrosina and Ferrell 1995). However, stump vulnerability to *H. annosum* basidiospores significantly decreases after a period of 2 weeks, as stumps become colonized by competing fungi. Hyphae from germinating basidiospores colonize the wood of the stump and lateral roots. Root grafts or contacts, where roots from two or more trees touch, can provide contact between infected and healthy trees and are a source of asexual spread of *H. annosum*. Infection centers can often be traced to larger stumps that were colonized soon after harvest. Stumps greater than 36 cm (14 inches) in diameter are more likely than smaller stumps to serve as foci of infection centers (Goheen and Otrosina 1998).

Incidence and severity of annosus root disease varies considerably, depending on site location and history of forest stands. In general, annosus root disease represents a more serious problem in managed forests than in natural forests (Shaw and others 1994). Previous studies have shown that higher levels of mortality are typically found in stands that have been partially cut and stands that have experienced multiple thinnings (Schmitt and others 1984). In one survey in Oregon, 89 percent of true fir stumps were colonized 5 to 9 years after harvest (Filip and others 2000). In the Inland West, this disease can cause substantial tree mortality, especially when associated with drought stress or insect attack (Filip and Morrison 1998). Trees infected with annosus root disease are frequently subject to attack by insects, such as the fir engraver beetle on true firs (Cobb and others 1974; Hertert and others 1975; Lane and Goheen 1979; James and Goheen 1981; Schowalter and Filip 1993) and mountain pine beetle or western pine beetle on pines (Cobb and others 1974). In northern Idaho and northeastern Washington, stands that are dominated by Douglas-fir can have large amounts of mortality, especially on dry sites (Lockman 1993; Schmitt and others 2000). *Heterobasidion annosum* can persist on a site and within stumps for long periods. In larger stumps, *H. annosum* can survive up to 60 years (Goheen and Otrosina 1998).

Disease Symptoms and Signs

Common symptoms of annosus root disease are the same as for many other root diseases and include yellowing or thinning of crowns, reduction in tree height and lateral branches, and stress cone crops. In firs, heartwood in butts and lower stems of infected trees are often stained red (fig. 7). Advanced decay includes stringy, spongy, and white-streaked areas that often have scattered black flecks (fig. 8). Decayed wood can also become laminated (separated along spring wood of growth rings) as it dries out.

Fruiting bodies occur in hollow stumps, on root crotches, or on root collars of dead and dying trees. Although rare or inconspicuous, fruiting bodies can be used for positive identification of the fungus. Conks are perennial and may appear to have several layers or furrows. In the early stages of development, these conks appear as small buff-colored cushions. In later stages, the conks are shelf-shaped, the upper surface is smooth and a darker brown than the cream-colored margin, and the undersides are cream-colored with tiny-pores (fig. 9). A layer of white fungal mycelium (ectotrophic mycelium) is occasionally seen growing on the exterior of infected roots. In the absence of other identification methods, wood samples held at high humidity produce distinctive asexual fruiting bodies (conidiophores and conidia). DNA-based methods are

Figure 7—Common staining and decay caused by *Heterobasidion annosum* as it appears in a cross section of hemlock. (Photo courtesy of W.G.Thies)

Figure 8—White pocket rot characteristic of wood decay caused by *Heterobasidion annosum.* White mycelium with black specks is a common sign of this disease. (Photo courtesy of J. W. Schwandt)

Figure 9—Fruiting bodies of *Heterobasidion annosum*, the cause of annosus root disease, are perennial and often found in recessed hollows of stumps and roots. These were observed on an uprooted grand fir. (Photo courtesy of R.C. Rippy)

also available to help identify *H. annosum* to species (Garbelotto and others 1999; Bahnweg and others 2002).

Disease Management

Protective measures have focused primarily on preventing the colonization of stumps by germinating basidiospores (Morrison and others 1989; Schmitt and others 2000; Johansson and others 2002). Chemical and biological treatments of stumps have been tested with varying levels of success (Driver 1963a,b; Edmonds and others 1969; Weir 1969; Driver and others 1970; Russell and others 1973a; Nelson and Li 1980; Woodward and others 1998). One boron-containing compound (sodium tetraborate decahydrate) has been widely used and can be successful for preventing colonization if applied within 48 hours after harvesting (Otrosina and Ferrell 1995; Schmitt and others 2000). Alternatively, in Europe, freshly cut stumps may be treated with urea, as this increases the pH of the stump surface to a level where basidiospores cannot survive (Brantberg and others 1996; Johansson and others 2002).

The potential for biological control of *H. annosum* has been the subject of limited investigations in Western North America (Filip and Morrison 1998). A fungal species, *Phlebiopsis gigantea* (=*Peniophora gigantea*), has been documented to out-compete *H. annosum* when applied to freshly-cut stumps (Rishbeth 1963; Woodward and others 1998). In Europe, use of this biological agent for controlling *H. annosum* is widespread, commercially available, and effective (Vainio and others 1998).

Stump removal can be effective for reducing buildup of root-rot fungi after tree removal; however, this method is expensive and can be disruptive to the site (Thies and others 1994; Roth and others 2000). Because *H. annosum* can behave as a wound parasite, wound prevention, especially during harvest, is a primary method of disease management (Goheen and others 1980; Aho and others 1983; Filip and others 1992b; Sullivan and others 2001). *Heterobasidion annosum* populations vary in their pathogenicity and host ranges, and hosts also vary in their ability to resist strains of the pathogen (Worrall and others 1983). This pathogen can be extremely damaging on sites planted with a single species. Thus, one approach used to manage annosus root rot is favoring mixed stands that include hardwoods or a mixture of conifers (Schmitt and others 2000).

Timing of management activities may be important, but results from different studies are in conflict. Thinning in summer or winter may be preferred over spring or fall. Thinning under warm temperatures may allow other fungi such as *Trichoderma viride* to out-compete *H. annosum* for establishment within the substrate of newly created stumps (Driver and Ginns 1969). Alternatively, if thinning occurs during winter when snow cover is present or temperatures are at or below freezing, the rate of stump colonization by *H. annosum* may be reduced and may favor colonization by other microorganisms (Chernykh and Belyi 1978). Studies in northeastern Oregon, however, found no difference in stump colonization by *H. annosum* among different harvesting seasons (Filip and others 1992a).

Fuels Treatment Considerations

Thinning may be one of the most important management practices that encourages the spread of *H. annosum* because it opens infection routes, creates fresh stumps for colonization by *H. annosum*, and creates logging wounds on standing trees that serve as infection sites for *H. annosum* (Aho and others 1983; Korhonen and others 1998; Sullivan and others 2001). On the other hand, one study showed that thinning in western hemlock stands increased sound-wood volume in residual trees despite minor logging wounds and *H. annosum*-caused decay (Goheen and others 1980). Also, wound prevention and stump treatments have been shown to greatly reduce *H. annosum* infection.

In pine stands in the Southeastern United States, annosus root disease has been reduced by prescribed burning prior to thinning operations. This burning reduces the duff layer that favors sporophore production, thus reducing the spore loads in the stand at the time of thinning (Froelich and others 1978; Otrosina and others 1995). However, successful tests of underburning for control of annosus root disease have not been reported for forests in the Inland West, perhaps because this treatment is typically considered impractical under the stand and soil conditions in this region. Research on the effects of prescribed fire on the incidence of stump-surface infection is needed in the Inland West.

Laminated Root Rot

Laminated root rot, caused by *Phellinus weirii* (Murr.) Gilb., is prevalent in British Columbia, Washington, Oregon, northern California, northern Idaho, and western Montana (Nelson and others 1981; Sturrock and Garbutt 1994; Thies and Sturrock 1995). *Phellinus weirii* is considered a "disease of the site" because it persists across tree generations (Hadfield and others 1986; Thies and Sturrock 1995). This disease can cause extensive growth loss and mortality that is often associated with windthrows within disease centers involving several conifer species of diverse age classes. The pathogen appears to spread by contact of susceptible tree roots with stumps or roots of previously infected trees. Laminated root rot is most destructive in stands 25 to 125 years old, and damage increases in subsequent stands (Tkacz and Hansen 1982).

In Western forests, highly susceptible species include Douglas-fir, grand fir, mountain hemlock, and white fir. Intermediately susceptible species include Engelmann spruce, Pacific yew, subalpine fir, western hemlock, and western larch. Species that are tolerant or resistant to laminated root rot include lodgepole pine, sugar pine, western white pine, ponderosa pine, and western redcedar; all hardwoods are immune (Filip and Schmitt 1979; Hadfield and others 1986; Nelson and Sturrock 1993; Thies and Sturrock 1995). Fire exclusion increases the proportion of shade-tolerant conifers, which are generally more susceptible to laminated root rot.

Phellinus weirii has two basic forms: one that produces a butt rot in western redcedar, and another that causes root disease in Douglas-fir and several other conifer species (Thies and Sturrock 1995). A proposal to change the scientific name of the form of *P. weirii* affecting Douglas-fir to *P. sulphurascens* (Larsen and Cobb-Poulle 1990) or *Inonotus sulphurascens* (Larsen and others 1994) has not been universally accepted. *Phellinus weirii* often occurs with other root diseases, such as Armillaria root disease and black stain root disease (Sinclair and others 1987). More than 4.4 million cubic meters (154 million cubic feet) of timber volume are estimated to be lost annually to laminated root rot (Nelson and others 1981).

Associations have been found between the occurrence of *P. weirii* and aspect, elevation, timber type, habitat type, and soil type. Soil characteristics, such as pH, temperature, and moisture content, may also affect the occurrence and extent of damage from laminated root rot (Thies and Sturrock 1995). Mortality due to this disease is generally higher on wetter than on drier habitat types.

Trees infected with *P. weirii* are sometimes killed by bark beetles in combination with other root diseases. The Douglas-fir beetle, Douglas-fir pole beetle, and fir engraver are commonly associated with laminated root rot (Schowalter and Filip 1993). Laminated root rot, as with other root diseases, provides a continuous source of suitable material for maintaining endemic bark beetle populations when conditions are not favorable for epidemics (Thies and Sturrock 1995).

Disease Symptoms and Signs

Infected trees exhibit crown symptoms typical of many root diseases: chlorosis, reduction in growth, gradual crown thinning, and a crop of stress cones. In wind-thrown trees, decayed roots are typically broken at the root collar; roots do not usually lift from the soil as the tree falls (fig. 10). This is especially noticeable in infection centers, where fallen trees may occur as a random pattern of crossed stems. Incipient decay in the roots and lower bole of infected trees usually gives a red-brown stain to the outer heartwood (fig. 11). Advanced decay separates easily into sheets at the annual rings; sheets contain small pits and are covered with reddish-brown to pinkish setal hyphae that can be seen with a hand lens (fig. 12). Gray-white to buff-colored mycelia may be found on the outer surface of infected roots. Fruiting bodies of *P. weirii* typically form near or in contact with the forest floor on the underside of downed trees and uprooted stumps. They have light gray-brown pore surfaces and margins that are white to cream-colored when young but later turn a uniform chocolate brown. However, fruiting bodies are of little diagnostic value, as they are uncommon and inconspicuous (Hadfield and others 1986; Sinclair and others 1987).

Disease Management

Identifying areas containing laminated root rot is the essential first step to successfully managing for this disease. After disease has been assessed, acceptable levels of disease must be determined before deciding upon a management response. To reduce disease impacts, thinning treatments can:

- Avoid areas with the disease.
- Selectively remove the most susceptible species.
- Favor root-disease resistant or tolerant species.
- Make openings in which to plant or regenerate root disease-resistant or tolerant species.
- Use push-felling to extract root systems from the soil (Bloomberg and Reynolds 1988; Morrison and others 1988).
- Include stump removal to reduce inoculum levels (Hadfield 1985; Hadfield and others 1986; Thies and Sturrock 1995).
- Include a combination of these treatments.

However, the potential adverse effects of soil compaction and tree wounding caused by heavy equipment must also be considered (Lull 1959; Froehlich and McNabb 1984; Smith and Wass 1991). Thus far, effects of treatments such as fertilization have supported increased growth of trees but produced no apparent reduction in disease-caused tree mortality (Thies and Nelson 1988). Eradication of *P. weirii* from infected stumps with fumigants (Thies and Nelson 1987) in conjunction with antagonistic *Trichoderma* (Nelson and Thies 1985, 1986; Nelson and others 1987) has been successful under experimental conditions but has not been used operationally in the United States. Increasing species diversity to

Figure 10—Laminated root rot mortality center showing characteristic root wads with roots broken near the root collar, leaving only stubs. (Photo courtesy of W.G. Thies)

Figure 11—Incipient decay from laminated root rot in the roots and lower bole of infected trees is frequently observed as a red-brown stain in the outer heartwood. (Photos courtesy of W.G. Thies)

Figure 12—White mycelium on the outer bark of infected root underneath the duff is a common characteristic of laminated root rot (upper left). Advanced decay from laminated root rot causes wood to separate easily along growth rings of spring-wood. Each layer of decayed wood has small pits and often displays cinnamon-brown mycelium with hairlike pegs that project away from the layer (upper right). The underside of this Douglas-fir log shows the appressed habit of the young fruiting bodies of *Phellinus weirii* (lower). (Photos courtesy of W.G. Thies and R.C. Rippy).

reduce losses associated with *P. weirii* is a preferred strategy in northern Idaho, western Montana, Oregon, and Washington (Hadfield and others 1986; Thies and Sturrock 1995; Filip 1999).

For additional information pertaining to *P. weirii* and its management, see Morrison and others (1992), Thies and Sturrock (1995), and Hansen and Goheen (2000).

Fuels Treatment Considerations

The effect of wildfire on *P. weirii* has been speculated to be more indirect than direct, as fire acts by changing stand species composition and forest successional patterns involving susceptible and resistant hosts (McCauley and Cook 1980). Because fire has little direct influence on the survival of *P. weirii* inoculum, fuels reduction by burn treatments, such as prescribed burning, are not likely to directly influence the occurrence of laminated root rot (Thies and Sturrock 1995). However, fuels treatments that would use prescribed burning at intervals that approximate historic fire frequencies, with the aim of converting stand composition back to an early successional stage, are strategies for management of this disease. From a production standpoint, thinning is generally not recommended in stands with a major component of susceptible trees and moderate to high levels of disease. In disease centers, thinning treatments without stump removal may increase disease severity. This approach is generally only considered when either a final harvest is scheduled within 15 years, or severe losses are deemed acceptable (Thies and Sturrock 1995).

Black Stain Root Disease

Black stain root disease is caused by three host-specialized, genetically isolated varieties of the pathogen *Leptographium wageneri* (Kendrick) Wingfield (Harrington and Cobb 1984, 1986, 1987; Zambino and Harrington 1989, 1990). The hard pine variety (var. *ponderosum)* is prevalent from the Pacific Coast States to the Northern Rockies, including all States and Provinces of the Inland West south and west of the Bitterroot Mountain range. This variety infects ponderosa, lodgepole, and Jeffrey pine and can also occasionally be found in hemlocks, white and Engelmann spruce, and white pines (Morrison and Hunt 1988; Allen and others 1996). The Douglas-fir variety (var. *pseudotsugae*) is broadly adapted to Douglas-fir from moist coastal to arid situations, from California to British Columbia to southern Colorado and New Mexico. The pinyon variety (var. *wageneri*) occurs on pinyon species, primarily singleleaf pinyon, throughout the Southwest to the southern edge of Idaho.

Stands affected by black stain root disease are generally moist to mesic. Disease incidence may be higher in areas with soil compaction, poor drainage (Hadfield and others 1986), or coarse-textured soils and shallow soils prone to summer drought (Morrison and Hunt 1988). The pinyon and hard pine varieties are limited to areas with cool soil temperatures, whereas the Douglas-fir variety can survive and infect at higher soil and bole temperatures. Black stain root disease occurs as persistent infection centers or as scattered infections after disturbances such as road building, construction, and thinning (Hansen 1978; Harrington and others 1983). Within infection centers, the pathogen spreads by growth in and along roots, by root grafting or root contact, and by limited hyphal growth (up to 15 cm) through the soil between roots (Cobb 1988). Infection can occur through natural openings in small roots, such as splits at root forks and sites where lateral roots emerge, or at the site of root injuries, such as caused by abrasion against rocks (Hessburg and Hansen 2000). Root lesions from *Armillaria* infections on adjacent trees can also allow transfer of the black stain root disease pathogen from host to host (Hessburg and Hansen 2000). Root damage caused by equipment can provide an abundance of infection courts. Experiments with inoculated Douglas-fir seedlings indicate that most minor root wounds no longer act as infection courts after 1 month, because wound closure prevents infection. The pathogen does not penetrate either intact parenchyma or callus (Hessburg and Hansen 2000).

Expansion of infection centers in the various hosts averages around 1 m/year (3.3 feet/year) (Hessburg and others 1995), with rates of up to 7 m/year (23 feet/year) reported in some pinyon stands (Cobb 1988). Even the slower rate is substantially (three to five times) faster than most other root diseases (Hessburg and others 1995). It appears that the black stain pathogen may be active in stumps for only 3 years after harvest, as it dies rapidly after the death of host tissues (Cobb 1988). Severity and rates of spread are positively related to density of hosts (Cobb 1988). In Douglas-fir, rates of infection center expansion decrease markedly after stands reach an age of 30 to 35 years (Hessburg and others 1995).

Unlike many root pathogens, infection centers of black stain root disease are established from initial infections vectored by root-feeding bark beetles and weevils (Goheen and Cobb 1980; Harrington and others 1985; Witcosky and Hansen; 1985; Witcosky and others 1986; Cobb 1988; Hansen and others 1988; Harrington 1988). Insect vectors are attracted to stressed trees (Harrington and others 1985; Morrison and Hunt 1988). Trees in decline due to black stain root disease are also predisposed to infestation by both root-inhabiting and bole-inhabiting species of bark beetles (Goheen and Cobb 1980; Cobb 1988; Hessburg and others 1995, 2001; Negron and Wilson 2003). Bark beetle species that vector the disease are attracted to volatiles given off by living roots of dying trees (Witcosky and others 1987; Kelsey and Joseph 1998). Once an insect has caused a tree to become infected, recent layers of xylem in the root system are colonized. Presence of persistent black stain root disease infection centers can maintain local populations of bark beetles, initiating bark beetle mortality centers (Cobb 1988).

Disease Symptoms and Signs

Crown symptoms that occur if black stain root disease is present in a stand include many typical above ground symptoms of root disease, such as reduced growth and fading of crowns, slow or rapid decline (slower in old trees and faster in young trees), distress cones, and crown wilt. Pines will usually succumb to bark beetle attacks before the latter symptom can be expressed (Cobb 1988). Because mortality can be hastened by bark beetles, and the crown symptoms of black stain root disease are similar to those of other root diseases, mortality caused by black stain root disease is sometimes mistakenly attributed to other causes (Cobb 1988; Hessburg and others 1995). However, stands with black stain root disease will have trees in different stages of mortality, typical of root disease infection centers, instead of a uniform onset of mortality, typical of mass attacks by bark beetles (Cobb 1988).

The most diagnostic sign of black stain root disease is the microscopic mycelium that is visible as dark purple to black staining in younger layers of sapwood in roots and the lower trunk of an affected tree (fig. 13). Unlike blue stain fungi, which are also vectored by insects, these streaks of intense staining in the bole strictly follow the path of xylem upward from the roots where the initial infection point occurred. In cross-sections of stems and roots, the staining has an arclike appearance, as it lies primarily within early wood of recently infected growth rings. This staining pattern further differentiates black stain root disease from blue stain, which develops in parenchyma rays at the time of mortality and extends in wedge-shaped patterns into heartwood (fig. 14). The restriction of black stain to recent rings results from fungal colonization of the tracheids of active xylem (Cobb 1988). These symptoms and the development of disease are similar to the vascular wilts of hardwoods (Joseph and others 1998).

Figure 13—Dark purple to black streaks of stain within the outer one to two annual rings of sapwood in the lower bole and roots of an affected tree indicate black stain root disease caused by *Leptographium wageneri*. (Photos courtesy of W.G. Thies and R.C. Rippy)

Figure 14—Arcs of stain (left) are typical of black stain root disease and are caused by *Leptographium wageneri* colonizing the tracheids of the most active growth rings. In contrast (right), fungi that cause blue stain colonize parenchyma rays to form wedgelike sections that penetrate to the limits of the sapwood. (Photos courtesy of W.G. Thies and R.C. Rippy)

Disease Management

Few long-term field studies have been conducted to assess the behavior of this disease over time in stands under different types of management. Nonetheless, indications from existing studies suggest that the disease may be minimized by maintaining stand vigor while avoiding disturbance and injury, especially during times of peak beetle activity (Hadfield and others 1986; Hessburg and others 1995). Maintaining trees in vigorous condition with adequate spacing has been suggested as the most useful long-term strategy for minimizing losses to black stain root disease (Cobb 1988).

Because black stain root disease is vectored by beetles, any activities that increase the numbers of vectors in an area have the potential to increase disease, if disease is already present in stands within flight distances of its vectors. The distance for concern is 1.6 km (1 mile) for insect vectors of Douglas-fir (Hansen and others 1988; Hessburg and others 1995). Black stain root disease has long been associated with road building (Goheen and Hansen 1978; Hansen 1978; Hessburg and others 2001) and thinning-associated disturbance (Harrington and others 1983; Hessburg and others 2001). Thinning of affected species can trigger increases in vector population and establishment of many new infection centers. Dramatic 20- to 100-fold increases in the most important of the three insect species that act as vectors in Douglas-fir have occurred following springtime precommercial thinning (Harrington and others 1985; Hansen and others 1988). Thinning and clearcutting in ponderosa pine in winter and spring also cause dramatic increases in vector beetles (Otrosina and Ferrell 1995). Management strategies for Douglas-fir have included preventing tree wounds, avoiding tractor logging within 1.6 km (1 mile) of an infection center, favoring a diverse stand composition that includes tree species that are not susceptible to the pathogen, and restricting thinning to summer after spring beetle flights (Hansen and others 1988; Filip 1999; Hessburg and others 1995, 2001). This ensures that vectors will be established in other dead or dying trees prior to thinning. Summer thinning also allows roots and stumps of newly cut trees time to dry out before fall (Witcosky and others 1986; Hessburg and others 1995; Filip 1999). Fall thinning is not recommended because stumps may still attract insects the following spring. A specific recommendation for minimizing disease by the hard pine variety of the pathogen is to maintain mixed conifer type forests where indicated by habitat, but limit susceptible pine species to 25 percent of the mix when disease is present (Cobb 1988). If stands of susceptible tree hosts have adequate spacing and are intermixed with nonsusceptible species, these stands will be at lower risk of becoming permanent infection centers and will have reduced tree-to-tree spread through roots. Because the pathogen has low persistence, healthy but susceptible trees outside the margins of infection centers have been felled to limit further expansion (Tainter and Baker 1996).

Fuels Treatment Considerations

Factors to consider prior to choosing a fuels treatment are whether black stain root disease occurs within the vicinity of the treatment area, which hosts are being affected, the ratio and spacing of host and nonhost trees, and the choice of season for fuels management treatments. In general, if a fuels treatment is necessary, the key for minimizing subsequent black stain root disease is to reduce wounding of residual trees, minimize compaction, and time activities in relation to insect dispersal activities. Little published information is available on the effects of prescribed fire in different seasons on host vigor and root diseases (Thies and others 2001). Research is needed to determine the degree to which insect vectors of black stain root disease are attracted to roots damaged by prescribed fire, whether the damage or attraction differs with the season during which the fire treatment is applied, and how long insect attraction persists. Thus, answers are likely to be complex, and must weigh the direct detrimental effects on hosts against the potential effects on disease and fire behavior. A study of ponderosa pine/juniper stands in the Blue Mountains of southeastern Oregon showed that all root- and lower bole-feeding insect species that could potentially act as vectors of black stain root disease were greater in abundance following prescribed burns than in unburned controls. Fall burning caused greater direct and delayed mortality than spring burning, but mortality was not due to black stain root disease (Thies and others 2001; Thies and others in press). Different species of root- and lower bole-feeding insects were favored by spring or fall burns, and no clear relationships between time-of-burn or transmission of black stain root disease had been identified at these sites (Thies and others 2001). Another study in the same location showed that fall burning caused significant reductions in both fine root biomass and ectomycorrhizal fungus species richness in stands of ponderosa pine, both important for tree health, whereas spring underburning had little effect (Smith and others 2004).

Schweinitzii Root and Butt Rot

Phaeolus schweinitzii (Fr.) Pat., also known as the velvet top fungus, causes Schweinitzii root and butt rot, a decay in the roots and lower stem that affects most mature coniferous tree species in Western forests (Hadfield and others 1986). It is the most common cause of brown-cubical rot in Douglas-fir and other commercial timber species (Gilbertson and Ryvarden 1987). Douglas-fir is the most common species infected, but ponderosa pine, lodgepole pine, western white pine, western redcedar, western larch, western hemlock, spruces, and true firs are also known hosts (Allen and others 1996; Hagle and others 2003). *Phaeolus schweinitzii* is regarded as the most serious butt-rot pathogen of conifers in old-growth forests in the United States (Sinclair and others 1987).

Windborne spores of *P. schweinitzii* colonize trees through basal scars caused by fire, wounds from logging, or through wounded roots. The pathogen might also spread between trees with root contact, but little direct evidence is available to support this theory (Sinclair and others 1987). This fungus usually infects and kills root tips, resulting in “stubbed” roots with blunt ends (Hagle and others 2003). Soil compaction, drought, and flooding may predispose roots to damage (Tainter and Baker 1996). Trees growing on sites with shallow soils or soils with low water-holding capacity are more likely to be damaged by *P. schweinitzii* (Beckman and others 1998). *Phaeolus schweinitzii* can grow through wood colonized by *Armillaria* species and may predispose trees to Armillaria root disease and bark beetles (Hadfield and others 1986; Sinclair and others 1987). Alternatively, *Armillaria* species may be a secondary pathogen that follows *P. schweinitzii* in Douglas-fir and grand fir in Idaho (Dubreuil 1981).

Decay is usually confined to the roots and lower 3 m (9.8 feet) of the bole. Trees with advanced Schweinitzii rot are predisposed to windthrow and breakage. Valuable butt logs are extensively decayed, causing serious losses in timber volume. Decay caused by *P. schweinitzii* may be confused with decay caused by *Fomitopsis pinicola*, *Fomes officinalis*, *Laetiporus conifericola*, and *Postia sericeomollis* (Partridge and others 1978; Allen and others 1996; Hagle and others 2003).

Disease Symptoms and Signs

Trees infected with *P. schweinitzii* rarely exhibit root-disease crown symptoms (Partridge and others 1978; Hadfield and others 1986; Hagle and others 2003). Carpenter ant infestation and/or bark beetle attacks may occur on trees weakened by this disease. Small-diameter roots that are infected may be “stubbed” with gall-like swellings and may have dark, resinous heartwood (Hagle and others 2003). Infected trees may also have pronounced swelling at the butt (Scharpf 1993).

Fruiting bodies are annual, developing in the late summer and fall, but may persist for a year or more (fig. 15). These fruiting bodies are found on the ground near infected trees or occasionally emerge directly from the stem of an infected tree (Hadfield and others 1986; Hagle and others 2003). Those that form on the ground are circular or irregularly lobed in form with a sunken center and short, central stalk; those forming on infected trees are shelflike. The upper surface is velvety, up to 25 cm (10 inches) in diameter, and usually reddish brown with a yellowish margin when fresh. The lower surface has large angular pores and is yellow-green when young, turning brown with age. Older fruiting bodies can resemble cow dung in appearance (Scharpf 1993; Hagle and others 2003). Incipient decay, though sometimes inconspicuous, often produces a yellow to red-brown discoloration in the heartwood. With advanced decay, wood becomes reddish brown, crumbly, and may crack into large cubical pieces. Decayed wood can be easily crumbled into fine powder. Thin, white mycelial mats are sometimes present in shrinkage cracks (Gilbertson and Ryvarden 1987; Hagle and others 2003).

Disease Management

To reduce infection by *P. schweinitzii*, care should be taken to avoid wounding of trees and minimize soil compaction during harvesting operations. Because Schweinitzii rot primarily impacts older trees, economic losses might be reduced by harvesting trees before they are overmature (Hadfield and others 1986). Because of possible windthrow (fig. 16), trees infected with *P. schweinitzii* in recreation areas and around buildings should be considered hazardous. Increment boring of the lower bole and roots of trees can be used to detect brown rot. At other sites, the degree of care used to prevent new disease may be less. However, the beneficial ecological roles of brown-rots should also be considered before selecting management activities. For example, brown-rotted logs once incorporated into the forest floor or mineral soil can act as moisture reserves for ectomycorrhizal root development in periods of drought, provide a source of N fixation, and/or improve soil physical properties (Harvey and others 1987; Page-Dumroese and others 1994; Jurgensen and others 1997).

Fuels Treatment Considerations

Prescribed fire hot enough to cause basal wounds on trees should be avoided. Infections can be reduced by minimizing tree wounding during thinning operations. Information is unavailable for other potential interactions of fuels treatments with Schweinitzii root and butt rot.

Figure 15—Fruiting bodies of *Phaeolus schweinitzii* form on the ground or cut stumps of affected trees. They are circular or irregularly lobed in form, with a sunken center and short, central stalk. Older fruiting bodies, such as in the lower photo, dry up and closely resemble cow dung—hence the common name "cow-pie fungus." (Photos courtesy of J.E. Stewart and W.G. Thies)

Figure 16—Trees infected with *Phaeolus schweinitzii* may break off above ground level, exhibiting characteristic brown cubical butt rot (left). *Phaeolus schweinitzii* decay 30.5 cm (12 inches) above ground level in fire scar (right). (Photos courtesy of R.C. Rippy and J.D. Rogers).

Other Root Diseases of Consideration in the Inland West

Other notable root diseases present in the Inland West are Tomentosus root disease, Rhizina root rot, and stringy butt rot. While Tomentosus root disease, also known as stand-opening disease, has been the subject of numerous studies in British Columbia and Ontario, less information has been reported on it for the Inland West. Published information is also quite limited for Rhizina root disease and stringy butt rot.

Tomentosus Root Disease

Tomentosus root disease is found throughout the temperate region of the northern hemisphere (Hunt and Unger 1994). In Oregon and Washington, Engelmann spruce is the most common host (Hadfield and others 1986). Lodgepole pine is an important host in other parts of the range, while true firs, western white pine, and Douglas-fir are occasional hosts (Hagle and others 2003). The fungal pathogen, *Inonotus tomentosus* (Fr.) Teng., primarily spreads slowly from host-to-host by root-to-root contact but it also spreads by spores (Lewis 1997). Because of the slow rate of spread, infection centers occur as clumps of dead trees in the landscape, with standing dead or windthrown trees surrounded by trees in various stages of disease progression (Lewis 1997).

The likelihood that Tomentosus root disease will occur on a site depends on species composition, stem density, and site characteristics, such as soil moisture and nutrient regime (Lewis 1997; Bernier and Lewis 1999). Tomentosus root disease is difficult to control once *I. tomentosus* has become established at a site. The fungus can utilize root and stump resources well after bole removal, allowing it to persist at least 30 years after timber harvest. In a study in Utah, *I. tomentosus* was isolated from 75 percent of stumps 20 years after cutting. It was also isolated from dead roots as small as 1.3 cm (0.5 inches) in diameter 9 years after cutting and up to 5.5 m (18 feet) away from an infected stump 20 years after cutting (Tkacz and Baker 1991). Postharvest burning did not reduce the incidence of *I. tomentosus*, as the fungus was recovered in the same proportion of stumps from burned and unburned areas.

Disease Symptoms and Signs—Classic root rot symptoms, including thinning crown, chlorotic foliage, and reduced height growth, are displayed by trees infected with *I. tomentosus* (Bernier and Lewis 1999). Crown symptoms may not develop until 50 percent of a tree's roots are infected, so it is difficult to recognize Tomentosus root disease until after it is well established (Filip 1986; Lewis 1997). Characteristics of the decay in the root and butt heartwood are diagnostic. Appearance ranges from a reddish-brown stain in the early stages of decay, to elongate, spindle-shaped white pockets separated by firm reddish-brown wood in advanced decay (Tkacz and Baker 1991; Hagle and others 2003). In spruce, disease caused by *I. tomentosus* can be differentiated from annosus root rot, because wood decayed by the former is firm, instead of spongy. Also, the annual conks of *I. tomentosus*, which are produced on the ground near infected trees, are readily distinguished from the perennial conks of *H. annosum*. Fruiting bodies of *I. tomentosus* are 5 to 12.7 cm (2 to 5 inches) in diameter, with velvety caps and short stems. The pore surface on the underside of the cap is yellow and cream-colored, and darkens with age (Hagle and others 2003).

Rhizina Root Rot

Rhizina root rot is a disease of burned sites that affects conifer seedlings. This disease is not responsible for large volume losses, but it can impact plantings and natural regeneration after fire (Ginns 1968; Morgan and Driver 1972). Spores of *Rhizina undulata* Fr.:Fr. are viable for up to 2 years, and spore germination is stimulated by fire (Gremmen 1971). After underlying or adjacent soils have been warmed by fire, pathogen spores will germinate quickly and colonize the recently sterilized soil. The pathogen may infect susceptible conifer seedlings and cause mortality within a growing season. Infection occurs when a susceptible conifer root contacts mycelium or strandlike rhizoids. Losses of up to 80 percent of planted stock have occurred (Callan 1993); however, an extensive survey of 277 burned clearcuts in western Washington and Oregon found that Rhizina root rot caused little damage (Thies and others 1979). Rhizina root rot does not occur at all sites exposed to fire. For this disease to occur, sites must have the pathogen (usually from past infections), acidic soils, and susceptible conifer roots. In a laboratory study, young seedlings of lodgepole pine, a fire-successional conifer species, displayed strong disease symptoms when exposed to an isolate of *Rhizina undulata* from British Columbia (Egger and Paden 1986). While the pathogenicity of this fungus was consistent and intense, field occurrences either go unrecognized or occur infrequently.

Disease Symptoms and Signs—Seedling symptoms are nonspecific and may be easily misidentified as other root diseases or drought. The presence of *Rhizina* fruiting bodies in the vicinity of a dead conifer seedling is reliable evidence of the pathogen's presence on the site. Fruiting bodies of this fungus are brown to black, crustlike and fleshy, slightly convex, and often have an undulating margin. The undersides of the fruiting bodies have root-like rhizoids at multiple locations, which attach them to the soil, host roots, and occasionally to other substrates in the soil. They can occur in groups or lines that follow buried substrates or parasitized roots (Ginns 1974).

Stringy Butt Rot

Perenniporia subacida (Peck) Donk. produces a white stringy butt rot in infected trees and may also be known as yellow root rot because of its distinctively colored mycelium (Hadfield and others 1986). It is most commonly associated with mature trees that are either suppressed or weakened (Hadfield and others 1986). True firs, western hemlock, western redcedar, Engelmann spruce, and white spruce are among the most susceptible of its many coniferous and deciduous hosts. *Perenniporia* *subacida* has been classified as a wound parasite, although it is unclear whether infection by spores or mycelium is primarily responsible for disease initiation (Zeglen 1997). Trees infected by *P. subacida* are subject to windthrow and mortality. Significant volume loss from stringy butt rot is not an important issue in the Inland West (Hadfield and others 1986).

Disease Symptoms and Signs—Initially, the decay appears as a light-brown heartwood stain. Distinctive yellow mycelial mats may be observed when sheets separate along the annual rings; these mycelial mats help identify the fungus as *P. subacida*. Progression of the decay leads to small white pits in the sheets of annual wood, but eventually only white spongy fibers with black flecks remain. Leathery, perennial fruiting bodies that are cream to yellow in color may occupy the underside of downed wood or the basal region of standing dead trees. Small, circular pores mark their surface (Gilbertson and Ryvarden 1987).

Disease Management and Fuels Treatment Considerations

Tomentosus Root Disease—The ability of *I. tomentosus* to colonize organic debris and remain on site for decades is an important characteristic of this root disease. The survival and spread of *I. tomentosus* in an infected stand may be exacerbated by stumps and dead roots created by thinning practices. These reservoirs of inoculum may never contact susceptible trees if susceptible spruce and pine species are not planted. By delaying the regrowth of susceptible species for 20 years after tree removal, roots and stumps may decay to a water-soaked condition that reduces the likelihood of new infections. At least one study indicates that *I. tomentosus* cannot be recovered from such material (Tkacz and Baker 1991). In some situations, stump removal may be a viable option. Thinning methods that minimize wounding of residual trees would also limit the establishment of new infections. Prescribed burning to reduce woody substrate would not likely kill all of the fungus that resides within root heartwood.

Standing or windthrown trees dead from or having Tomentosus root disease contribute to fuel loading and may provide substrate for spruce beetles. One study reported that diseased trees were not predisposed to attack and may have helped to maintain spruce beetle populations at low levels (Lewis and Lindgren 2002). Infected trees can live 15 to 20 years before mortality occurs. The gradual decay of the roots makes infected trees subject to windthrow and a hazard concern for recreation areas.

Rhizina Root Rot—Even without seedlings to infect and parasitize, *Rhizina undulata* has the ability to use woody debris as a nutrient source. The fungus *Rhizina* may actually aid the decomposition of some smaller organic debris (Callan 1993). Described as only weakly saprotrophic, it is not known how long the fungus can remain on site without a living host.

In the past 15 years, no new research has been published on Rhizina root rot in the Inland West, so little is known about the interaction of fuels treatments, fire, and Rhizina root rot. If susceptible conifer seedlings were to be planted, it would be important to reduce spore germination by minimizing the areas of soil subject to warming. One possible strategy would be the use of "pile and burn" practices for removing hazardous fuels. More studies are needed to determine the scope of this disease in the Inland West and appropriate fuels treatments on sites with this disease.

Stringy Butt Rot—With so many hosts susceptible to infection by *P. subacida*, the best methods to manage stands infected with stringy butt rot are to prevent the creation of wounds that facilitate new infections on healthy trees and to remove diseased trees during thinning. The effects of fuels treatments and fire on stringy butt rot have not been well studied. Not enough is known about the distribution of this disease and the extent of its impact on the Inland West. Additional research studies are needed to determine impacts of fuels treatments on this disease.

Summary of Fuels Management Considerations

Before prescribing fuels treatments, managers should know whether root diseases are present and where they are located on a site. For conifer forests of the Inland West, root diseases caused by *A. ostoyae*, *H. annosum*, *Phellinus weirii*, *L. wageneri*, and *Phaeolus schweinitzii* are of special concern because of the extreme damage and mortality they can cause. The interactions between trees, root pathogens, and environment are complex and vary by forest structure, stand history, habitat type, species composition, soil characteristics, bark beetle populations, and activity of other forest insects and pathogens. It is not uncommon to have more than one root disease present in a stand.

Fuels treatment options should consider past management practices and their effects on current stand conditions. Seral species tend to be tolerant of root diseases but have declined in many areas of the Inland West. In northern Idaho, the combined effects of blister rust, selective harvesting, planting practices, and fire exclusion have reduced stand representation of white pine, western larch, and ponderosa pine but increased those of root disease-susceptible Douglas-fir and true firs (Beckman and others 1998; Filip 2002). On sites with mixed species composition—where seral and climax species co-occur with root disease organisms—infection and mortality of susceptible species have the potential to prolong the seral phase. This can favor the seral species that are tolerant to root disease unless late seral or climax species have been favored by management (Meyer 2004).

Use of a single type of treatment will not be appropriate for all forest conditions and root diseases. Some fuels treatments may increase root disease incidence, so managers should decide at the outset of planning what levels of mortality and growth loss will be acceptable. Estimates of treatment effects on mortality will be important for making subsequent estimates of changes in surface and ladder fuels. Tree mortality may be attributed directly to the root disease or to indirect consequences of infection, such as susceptibility to bark beetle attack. Killed trees can persist as standing snags or as windthrows, and may increase the overall amount of woody debris. Thus, fuels reduction treatments that cause increases in root disease mortality will likely increase the accumulation of fuels.

Acceptable options for fuels treatments differed among the diseases included in this paper. Thinning may increase damage from some root diseases, such as Armillaria root rot, laminated root rot, and annosus root disease. Incidence of black stain root disease and Schweinitzii root and butt rot may be less affected by this management practice if specific guidelines are followed. For all root diseases, care should be taken to avoid wounding of trees during timber harvesting or prescribed fire to reduce future impacts on stand health. Thinning treatments should also favor the species most tolerant to root disease and be timed to avoid problems with bark beetles. For example, regarding annosus root disease, biological and chemical control applied at the time of thinning could be effective for preventing new infections. Little information is available on the effects of prescribed fire and when it should be applied (seasonally) to decrease the effect of most root diseases.

Despite the importance of these issues, research regarding interactions of fuels treatments with root diseases has been limited. For this reason, much of the information presented here has been based on general principles of forest pathology. More precise information for specific sites, diseases, and host trees would be desirable to optimize fuels treatments with stand conditions and locations. To determine the most suitable forest management practices for the Inland West, more studies are needed on the interactions among fuels treatments, fire, and root diseases.

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