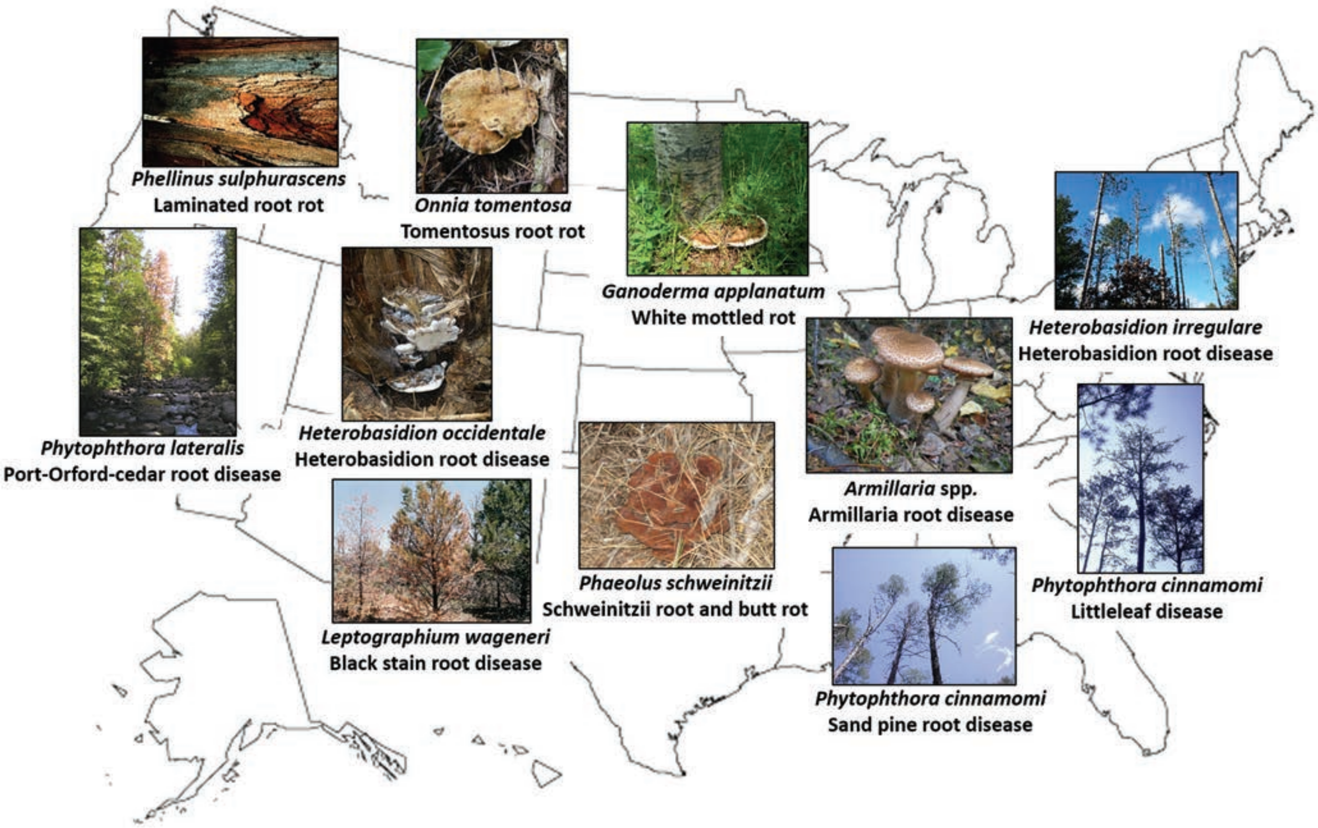
United States Department of Agriculture

Forest Root Diseases Across the United States



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Abstract

The increasing importance and impacts of root diseases on the forested ecosystems across the United States are documented in this report. Root diseases have long-term impacts on the ecosystems where they reside due to their persistence onsite. As a group of agents, they are a primary contributor to overall risk of growth loss and mortality of trees in the lower 48 States. Root diseases kill trees, decay wood, slow tree growth, predispose trees to other mortality agents, and cause trees to fail or fall over. In this manner, these diseases reduce timber volume, alter forest composition and structure, impair ecosystem function, and decrease carbon sequestration. Root diseases cause tree failures that can result in serious injury, damage, or death, and are thus important components in hazard tree management. Without adequate knowledge of root diseases and their roles in forested ecosystems, our ability to manage their negative impacts and build resilient forest landscapes is severely compromised.

Keywords: *Armillaria, Heterobasidion, Leptographium, Onnia, schweinitzii, Phellinus sulphurascens, Phytophthora, Ganoderma*

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Forest Root Diseases Across the United States

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Pesticide Precautionary Statement

This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate state or federal agencies, or both, before they can be recommended.

CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife—if they are not handled or applied properly. Use all pesticides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers.

Executive Summary

Summary

- Root diseases are the most damaging group of forest diseases in the United States (fig. 1).
- Root diseases, as a group of agents, are one of the three primary contributors to overall risk of tree mortality in the lower 48 States, according to the National Insect and Disease Forest Risk Assessment (NIDFRA) (Krist et al. 2014).

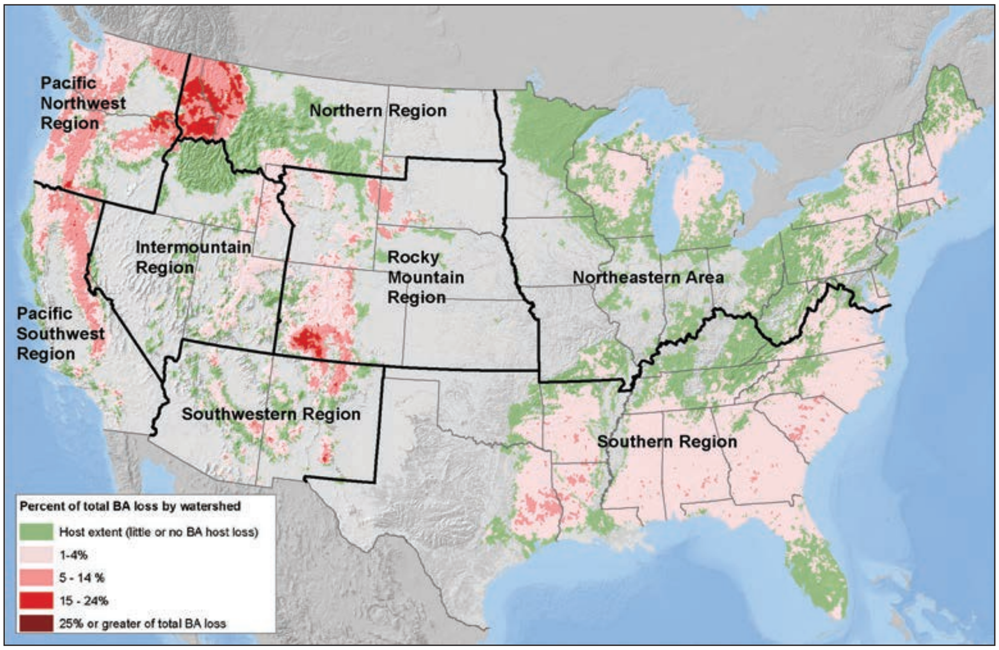

Figure 1—Root diseases are predicted to cause extensive mortality across the contiguous United States over the next 15 years. Root diseases have an impact in Alaska and Hawaii, but there are too few data for modeling risk from root diseases in those States. (Krist et al. 2014).

- Root diseases have long-term impacts on forest ecosystems due to their persistence onsite.
- All forest types and tree species are affected by one or more root diseases.
- Root diseases kill trees, decay wood, slow tree growth, predispose trees to other mortality agents, and cause trees to fail or fall over.
- Root diseases reduce timber volume, alter forest composition and structure, impair ecosystem function, and decrease carbon sequestration.
- Root diseases alter forest biodiversity and wildlife habitat by creating canopy openings, snags, and down woody material, which could have either a positive impact or a negative impact on wildlife.
- Root diseases cause tree failures that can result in serious injury, damage, or death, and are thus important components in hazard tree management.

Background

- Most root diseases are caused by fungi; the exceptions are those caused by *Phytophthora* species, which are water molds.

- Most root diseases decay lignin and cellulose in tree roots, compromising water and nutrient uptake and vertical stability of infected trees.
- Damage from root diseases is chronic and can develop over long periods, frequently without readily visible symptoms, so is not easily detected by aerial detection surveys.
- Root diseases, as a group of agents, are predicted to cause **well over 1 billion ft^2 (93 million m^2) of basal area mortality over 15 years** (2013 to 2027) (Krist et al. 2014). This damage amounts to the death of 1.4 billion trees of 12 inches (30.5 cm) diameter at breast height—more than the damage predicted for oak decline/gypsy moth, mountain pine beetle, or southern pine beetle (fig. 2).

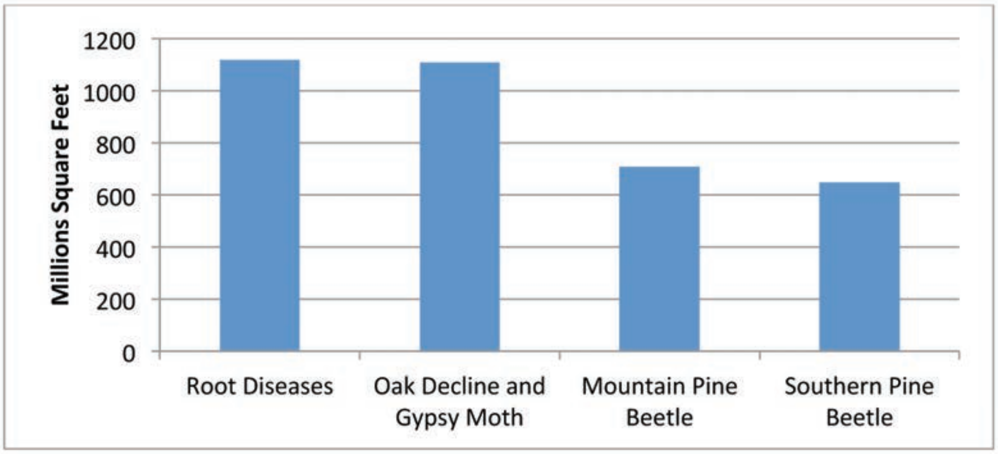

Figure 2—Root diseases are among the greatest mortality risks to forests in the United States, predicted to cause more than 1 billion ft^2 (93 million m^2) of mortality over 15 years (2013–2027) (Krist et al. 2014).

Future Direction and Needs

- Techniques to measure distribution and severity of root diseases are very limited or even nonexistent in some locations. Newer technologies need to be evaluated to improve our ability to recognize root diseases and measure their impacts over large areas.
- Long-term monitoring is necessary to properly measure and evaluate the impacts of root diseases on growth and mortality of host trees, site factors that affect presence and severity, and interactions between root diseases and other biotic and abiotic agents. As our nation's forests begin to undergo the stresses of climate change, long-term monitoring will become even more crucial for evaluating root diseases and other agents.
- Information on the basic biology of some of the root disease organisms is lacking. The role of many of these organisms and their function within the ecosystems they occupy are not well understood.
- Some sites are so severely affected by root diseases that the current forest cannot be economically managed, and restoration funding becomes necessary to shift forest composition to root-disease-tolerant species.

- Without adequate knowledge of root diseases and their roles in forested ecosystems, our ability to manage their impacts and build resilient forest landscapes is critically compromised.

Highlights by U.S. Forest Service Region

For each U.S. Forest Service region (see fig. 1), the extent of forest land area at greatest risk of losses from root diseases and the effects of the most prevalent root diseases are summarized below.

Northern Region (R1)

- Root diseases will put 7.6 million acres (3.1 million ha) at risk of losing 15 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- Of the 7.6 million acres (3.1 million ha) most threatened by root diseases, 1 out of every 4 acres or hectares (a total of 1.9 million acres, or 769,000 ha) is at risk of losing 25 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- Armillaria root disease, Heterobasidion root disease, laminated root rot, schweinitzii root and butt rot, and tomentosus root rot are the main root diseases in this region.
- According to data collected by the U.S. Forest Service, Forest Inventory and Analysis (FIA) crews, nearly 5.8 million acres (2.3 million ha) are currently infested with one or more root diseases (fig. 3), which cause an estimated loss of more than 166 million ft^3 per year (4.7 million m^3 per year).
- Factors contributing to this high level of root diseases are fire suppression shifting species composition toward species susceptible to root diseases and the introduction of white pine blister rust, which has significantly reduced the amount of western white pine, a root-disease-tolerant species.

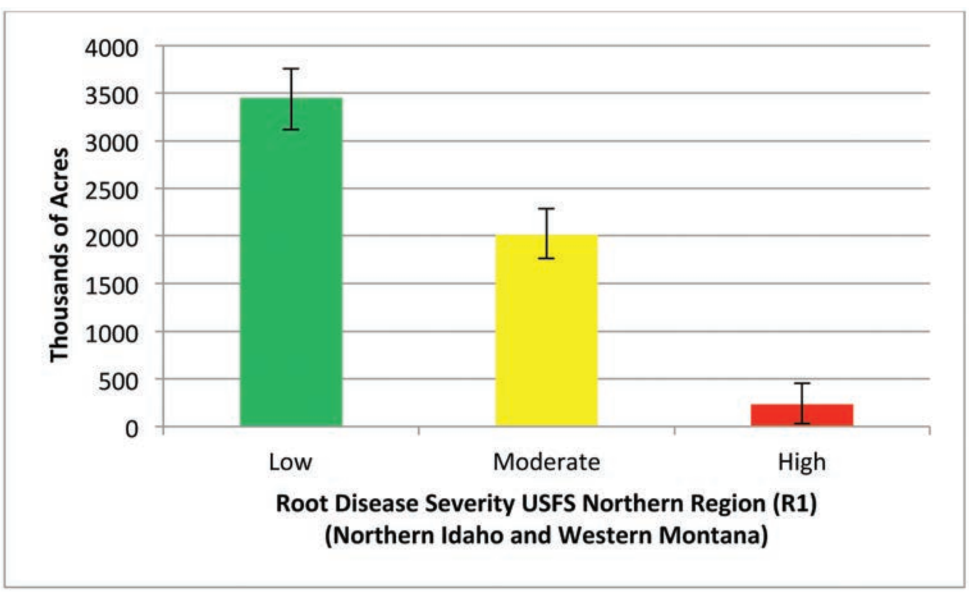

Figure 3—Acres of forest land affected by root diseases, by root disease severity class, in the Northern Region (R1). Nearly 5.8 million acres are currently infested with some level of root diseases as determined by aboveground symptoms (Lockman et al. 2015).

Rocky Mountain Region (R2)

- Root diseases will put more than 2.3 million acres (930,000 ha) at risk of losing 15 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- Of the approximately 2.3 million acres (930,000 ha) most threatened by root diseases, 1 out of every 7 acres or hectares (a total of 310,000 acres, or 125,000 ha) is at risk of losing 25 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- Armillaria root disease has its greatest impact in spruce/fir and mixed-conifer forests.
- Heterobasidion root disease can be found within the range of white fir in Colorado, and occurs in pines in central Nebraska.
- Black stain root disease infests 2 to 4 percent of pinyon pine stands in southwestern Colorado (fig. 4), causing losses of more than 60 percent on infested sites.
- White mottled rot occurs in aspen throughout the region, causing significant hazards in recreation sites.
- Schweinitzii root and butt rot and tomentosus root rot also contribute to the damage in this region.

Figure 4—Black stain root disease mortality center in a pinyon pine stand in southwestern Colorado (photo: H. Kearns, U.S. Forest Service).

Southwestern Region (R3)

- Root diseases will put more than 830,000 acres (336,000 ha) at risk of losing 15 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- Of the approximately 830,000 acres (336,000 ha) most threatened by root diseases, 12,000 acres (4,800 ha) are at risk of losing 25 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- Armillaria root disease contributes to dieback and mortality in old-growth spruce/fir forests and has the greatest impact on white fir.
- Heterobasidion root disease occurs on 9 percent of mixed-conifer forests and 14 percent of spruce/fir forests (fig. 5).

Figure 5—Stump-centered mortality caused by Heterobasidion root disease (photo: U.S. Forest Service).

- Tomentosus root rot in spruce is a serious problem in recreation sites with infected trees.
- White mottled rot occurs in aspen throughout the region, causing significant hazards in recreation sites.

Intermountain Region (R4)

- Root diseases will put more than 108,000 acres (44,000 ha) at risk of losing 15 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- Armillaria root disease is found on cool, moist alpine sites, infecting mainly true firs.
- Tomentosus root rot (fig. 6) occurs in spruce forests, causing pockets of disease and mortality, which are especially challenging on recreation sites.
- White mottled rot is common in older aspen stands and causes tree failure.
- Heterobasidion root disease commonly occurs in spruce/fir forests, causing lower-stem decay and windthrow.

Figure 6—Tomentosus root rot causes significant decay in roots and basal stem wood of live, standing trees (photo: B. Lockman, U.S. Forest Service).

Pacific Southwest Region (R5)

- Root diseases will put more than 1 million acres (405,000 ha) at risk of losing 15 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- More than 8 million acres (3.2 million ha) of commercial forest land on all ownerships are adversely affected by some level of root disease.
- Heterobasidion root disease is estimated to infect more than 12 percent of California's 16 million acres (6.5 million ha) of commercial forest land, with annual losses estimated at 9.25 million ft^3 (262,000 m^3).
- Eighteen percent of true fir stands are negatively affected by Heterobasidion root disease.
- Twenty percent of pine stands in eastern California have been deemed nonproductive due to infection by Heterobasidion root disease.
- Port-Orford-cedar root disease (fig. 7), caused by a nonnative, invasive pathogen, has infested about 9 percent of Port-Orford-cedar forest types.
- Basic information on the distribution and impacts of root diseases for Hawaii is severely lacking.

Figure 7—Dead and dying Port-Orford-cedar along a California waterway infested with Port-Orford-cedar root disease (photo: D. Owens, California Department of Forestry and Fire Protection, used with permission).

Pacific Northwest Region (R6)

- Root diseases will put almost 2.8 million acres (1.1 million ha) at risk of losing 15 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- Of the approximately 2.8 million acres (1.1 million ha) most threatened by root diseases, 47,000 acres (19,000 ha) are at risk of losing 25 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- Armillaria root disease, Heterobasidion root disease, laminated root rot, and Port-Orford-cedar root disease are the biggest contributors to damage.
- The largest known centers of Armillaria root disease mortality occur in this region (fig. 8).
- In eastern Oregon, 30 percent of ponderosa pine and nearly 100 percent of true fir stands are infested with Heterobasidion root disease.
- Laminated root rot causes mortality on 5 to 16 percent of Douglas-fir forest types in western Oregon.
- Port-Orford-cedar root disease, caused by a nonnative, invasive pathogen, has infested about 9 percent of Port-Orford-cedar forest types.

Figure 8—Mortality pocket caused by Armillaria root disease, U.S. Forest Service, Pacific Northwest Region (photo: G. Filip, U.S. Forest Service).

Southern Region (R8)

- Root diseases will put more than 1.6 million acres (647,000 ha) at risk of losing 15 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- Of the approximately 1.6 million acres (647,000 ha) most threatened by root diseases, 1 out of every 9 acres or hectares (a total of 310,000 acres, or 125,000 ha) is at risk of losing 25 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- Heterobasidion root disease is predicted to cause losses of more than 15 percent of the pine basal area on 2.9 million acres (1.2 million ha) between 2013 and 2027.
- High losses from Heterobasidion root disease (fig. 9) are related to the shift in tree species from longleaf pine to loblolly pine.

Figure 9—Canopy openings due to mortality from Heterobasidion root disease-caused mortality in planted pine in Texas (photo: G. Mason, U.S. Forest Service).

- Littleleaf disease (fig. 10) is found on 35 percent of the commercial range of shortleaf pine, infesting 1.4 million acres (567,000 ha) and causing estimated losses of more than $15 million per year.
- Red root and butt rot affects mature and old-growth pine trees, slash pine infected with fusiform rust, and eastern white pine plantations older than 30 years.

Figure 10—Impacts of littleleaf disease on shortleaf pine, U.S. Forest Service, Southern Region (photo: U.S. Forest Service, Bugwood.org).

Northeastern Area (R9)

- Root diseases will put nearly 430,000 acres (174,000 ha) at risk of losing 15 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- Of the almost 430,000 acres (174,000 ha) most threatened by root diseases, 1 out of every 3 acres or hectares (a total of 135,000 acres, or 55,000 ha) is at risk of losing 25 percent or more of total basal area between 2013 and 2027, according to NIDFRA predictions (Krist et al. 2014).
- Heterobasidion root disease is well distributed in New York and causes damage in thinned pine stands in Michigan and Wisconsin.
- Armillaria root disease readily infects stressed trees and is often associated with declines caused by interacting agents.

Alaska Region (R10)

- Basic information on the distribution and impacts of root diseases is severely lacking.
- Heterobasidion root disease is known to occur in southeast Alaska in old-growth western hemlock and Sitka spruce forests.
- Tomentosus root rot is thought to be widespread throughout spruce stands in south-central and interior Alaska.
- Armillaria is known to occur in many forest types, hastening the death of stressed trees.

Contents

Introduction

Root diseases are the most damaging group of diseases that cause volume loss of forest trees in the United States (Krist et al. 2014). All forest types and tree species are affected by one or more root diseases. These pathogens kill trees, decay wood, slow tree growth, predispose trees to other damaging agents, and cause trees to break or fall over. As a result, root diseases affect timber volume (Smith 1984), forest composition and structure, ecosystem function (Hagle et al. 2000), personal safety (Filip and Goheen 1982a; International Tree Failure Database 2010), and carbon sequestration (Raymond et al. in review; Washington State Academy of Sciences 2013). All but one of the root diseases discussed in this paper are caused by native pathogens, and as such they have been long-term associates of the forest tree species they affect and enduring components of the forest ecosystems they occupy. Management practices, fire suppression, climate change, and the introduction of exotic tree pathogens probably have altered the historic roles of root diseases and, in many cases, exacerbated their effects.

Most root diseases are caused by fungi that typically decay lignin and cellulose in roots of host trees, thus compromising the trees' ability to absorb water and nutrients and often leading to tree failure when structural roots become severely decayed (Manion 1991). Root pathogens may also invade and block crucial water-conducting tissues and create necrotic lesions in the phloem that eventually girdle and kill host trees. By weakening host trees, root diseases can predispose them to windthrow and other mortality agents, such as bark beetles (Scolytinae subfamily) or drought. Root diseases also affect the growth of host trees, and major growth impacts often occur before a tree displays symptoms of infection aboveground (Cruickshank et al. 2011; Thies 1983).

Root disease pathogens have long-term impacts on the forest ecosystems they occupy due to their longevity onsite (Hagle et al. 2000), and today's forests most likely reflect millennia of effects from root diseases. These pathogens can remain on the site long after infected trees die. They survive saprophytically in root systems for years to decades, thus becoming relatively permanent components of the site. This long-term site occupancy by root pathogens, along with such factors as aspect, soils, and moisture regimes, can affect the productivity of a site. Site productivity is generally reduced due to growth loss and mortality of host trees, which in turn affects carbon sequestration. By selectively removing susceptible host trees and leaving tolerant or resistant species, root diseases often change successional pathways by altering forest structure and composition. Conversely, these openings also allow for increased diversity in structure and species of plant life (Hansen and Goheen 2000; Kearns and Jacobi 2005). In addition to creating canopy openings, root diseases create snags and down woody material, all of which affect wildlife habitat.

Root diseases also threaten personal safety and property in the form of hazard trees (Filip and Goheen 1982a; Marosy and Parmeter 1989). Hazard trees are trees that pose a major safety risk because of their propensity to fall due to mechanical failure, often as a result of root decay. Root diseases also have a large but unmeasured impact on recreation sites (Filip et al. in preparation).

Most root-disease pathogens spread from infected root systems to the roots of neighboring trees via root-to-root contact or pathogen growth between adjacent root systems. Year after year, root diseases kill millions of trees across the United States within large pockets of mortality or as scattered small groups or individual trees, thereby causing long-term openings in the forest canopy. Root disease fungi occupy roots of infected trees and most remain onsite for years to decades after death of the host, ready to infect subsequent generations of trees. Consequently, damage from root diseases is chronic and protracted.

As a group of agents, root diseases are predicted to cause mortality of more than 1 billion ft^2 (93 million m^2) of tree basal area by 2027 (Krist et al. 2014). This volume is equivalent to the death of 1.4 billion trees of 12 inches (30.5 cm) diameter at breast height. Year-to-year changes in damage from root diseases are not easily detected and are often overshadowed by more fast-acting agents, such as bark beetles. However, cumulative losses from root diseases are predicted to be greater than losses from other agents, such as oak decline/gypsy moth (*Lymantria dispar* Linnaeus), pine beetles (*Dendroctonus* spp.), or fire (fig. 11), and damage from root diseases is predicted to increase under current climate change scenarios (Kliejunas 2011; Kliejunas et al. 2009; Klopfenstein et al. 2009; Washington State Academy of Sciences 2013).

An example from research on forest land in the U.S. Forest Service's Northern Region illustrates the severity of damage from root diseases compared to other agents. In northern Idaho and western Montana, forested land area affected by root diseases has been calculated to be more than 5.7 million acres (2.3 million ha) as determined by aboveground symptoms on U.S. Forest Service, Forest and Inventory Analysis (FIA) plots (Lockman et al. 2015). Based on these acreage estimates, the volume lost from all root diseases in northern Idaho and western Montana is estimated to be almost 166 million ft^3 (4.7 million m^3) per year. In contrast, volume lost to mountain pine beetles (*Dendroctonus ponderosae* Hopkins) and fire combined is estimated to be just over 150 million ft^3 (4.2 million m^3) per year (average from 2000 to 2009), even including the current mountain pine beetle epidemic (Kegley et al. 2011). Furthermore, previous studies have shown that root disease commonly predisposes trees to attack by mountain pine beetles (Bartos and Schmitz 1998; Fuller 1983; Goheen and Hansen 1993; Kulhavy et al. 1984; Tkacz and Schmitz 1986).

Several models were used to project impacts from root diseases and the results were compiled in the 2013–2027 National Insect and Disease Forest Risk Assessment (NIDFRA) (Krist et al. 2014) (fig. 12). Risk is defined as the expectation that 25 percent or more of the host basal area will be lost over the next 15 years, though risk is also reported in the

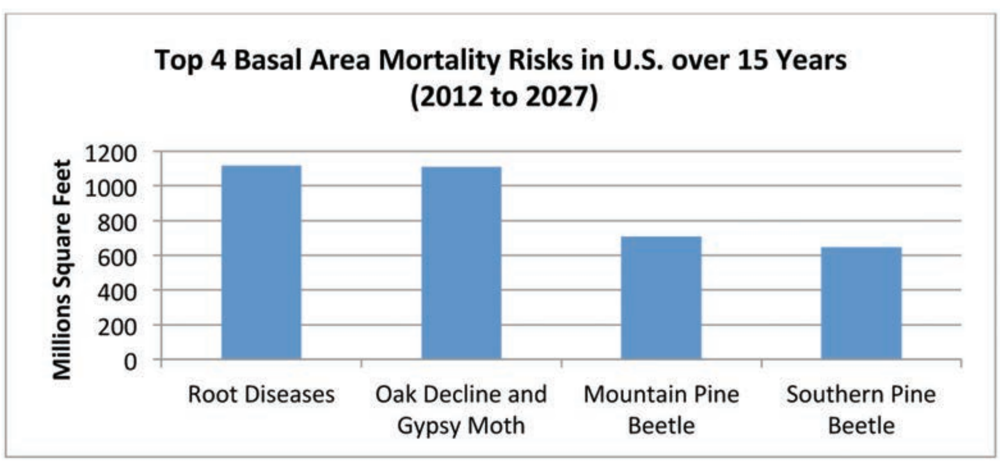

Figure 11—Root diseases are among the greatest mortality risks to forests in the United States, predicted to cause more than 1 billion ft^2 (93 million m^2) of mortality over 15 years (Krist et al. 2014).

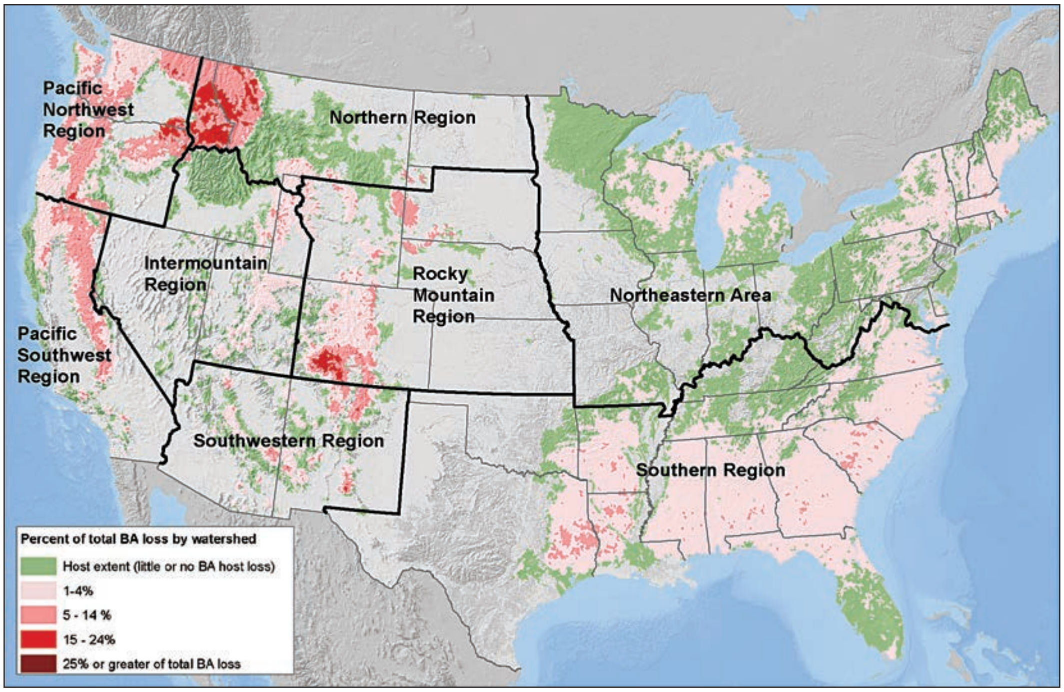

Figure 12—Root diseases are predicted to cause extensive mortality across the contiguous United States over the next 15 years (Krist et al. 2014). Root diseases have an impact in Alaska and Hawaii, but there are too few data for modeling risk from root diseases in those States.

following categories of loss: no loss, 1 to 4 percent loss, 5 to 14 percent loss, 15 to 25 percent loss, and 25 percent or greater loss (Krist et al. 2014). Root diseases as a group are one of the three primary contributors to overall risk of mortality in the lower 48 states, according to the NIDFRA models (figs. 11 and 12). Although root diseases are known to affect forested lands in Alaska and Hawaii, basic information about the distribution and impacts of root diseases is lacking for these States, so risk could not be calculated.

The NIDFRA models predict that during the 15-year period from 2013 to 2027 root diseases will put almost 2.6 million acres (1 million ha) at risk of losing 25 percent or more of total basal area across the United States. The risk of predicted basal area loss of 25 percent or more varies by U.S. Forest Service region (Krist et al. 2014) (fig. 12). The Northern Region has the most acreage at risk of the largest expected basal area loss with 1.9 million acres (769,000 ha), and the Rocky Mountain Region has more than 310,000 acres (125,000 ha) at risk of the highest basal area loss. The Southern Region has about 170,000 acres (69,000 ha) and the Northeastern Area has nearly 135,000 acres (55,000 ha) in the highest predicted basal area loss category. The Pacific Northwest Region and Southwestern Region have fewer acres at risk of the highest basal area loss, with 47,000 acres (19,000 ha) and 12,000 acres (4,800 ha), respectively. The Pacific Southwest and Intermountain Regions have very few acres with predicted basal area losses of 25 percent and greater. However, basal area losses of 15 to 24 percent are predicted on more than 1 million acres (405,000 ha) in the Pacific Southwest Region and more than 108,000 acres (44,000 ha) in the Intermountain Region. As mentioned above, basic information on the distribution and impacts of root diseases is severely lacking in the Alaska Region, so risk of root disease-related losses was not modeled for this region.

The agents modeled in NIDFRA to calculate risk from root diseases were Armillaria root diseases, Heterobasidion root diseases, laminated root rot, and Port-Orford-cedar root disease. This paper discusses these four root diseases, as well as others that have significant impacts across the United States (table 1 and see the earlier section on "Highlights by U.S. Forest Service Region" for regional summaries). *Armillaria* species are widespread across the country and cause the most damage in the Pacific Northwest and Northern Regions. *Heterobasidion* species are also widely distributed; they cause significant losses in the Southern and Pacific Southwest Regions and are having an increasing impact in the Pacific Northwest and Northern Regions. *Heterobasidion irregulare* causes damage in the Lakes States and localized areas elsewhere in the Northeastern Area. *Leptographium* species are broadly distributed but have the most impact in the western regions. *Phellinus sulphurascens* is restricted to the Pacific Northwest and Northern Regions, where it is considered the most important individual natural disturbance agent in affected areas (Hansen and Lewis 1997). Diseases caused by *Onnia* species and *Phaeolus schweinitzii* are widely distributed throughout the United States but represent more of a problem as decay agents of structural roots in the West and the Southern Region and spruce plantations in the Lake States. *Ganoderma applanatum* affects aspen stands, and causes notable damage in the Rocky Mountain Region. *Phytophthora* species affect pine forests in the Southern Region. The exotic *Phytophthora lateralis* causes a significant root disease in Port-Orford-cedar in the coastal areas of Oregon and California. Recent research suggests species of *Phytophthora* are also involved in widespread declines of oak in the East.

In 1984, Smith estimated the volume of timber lost annually to root diseases in the western United States to be 237.4 million ft^3 (6.7 million m^3). This volume accounted for about 18 percent of the total mortality in the western United States at that time. Impacts of root diseases nationwide have not been assessed since that report, although regional and local estimates have been made (Byler et al. 1990; Hansen and Goheen 2000; James et al. 1984). The purpose of this paper is twofold: to update the information in Smith (1984) and to document the importance of root diseases and the impacts they are having on U.S. forest ecosystems.

Armillaria Root Disease *Armillaria* Species

Biology and Ecology

Armillaria species are among the most damaging and broadly distributed forest tree pathogens in the world and the contiguous United States (fig. 13) (Shaw and Kile 1991; Tainter and Baker 1996). Several species in the genus *Armillaria* are pathogenic to varying degrees to North American conifers and hardwoods of all ages. *Armillaria ostoyae* (Romagn.) Herink, Herink, J.,[1] *A. mellea* (Vahl: Fr.) Kummer, *A. calvescens* Bérubé &

[1] An earlier classified species, *A. solidipes* Peck, has been proposed to replace *A. ostoyae* (Burdsall and Volk 2008), but a vote is pending to conserve *A. ostoyae* taxon (Hunt et al. 2011; Redhead et al. 2011).

Table 1—Root disease pathogens and the U.S. Forest Service regions in which they have significant impact.

USFS region name (numeric designation)	Armillaria root disease (*Armillaria* spp.)	Heterobasidion root disease (*Heterobasidion* spp.)	Laminated root rot (*Phellinus sulphurascens*)	Black stain and related root diseases (*Leptographium* spp.)	Schweinitzii root and butt rot (*Phaeolus schweinitzii*)	Tomentosus root rot and red root and butt rot (*Onnia* spp.)	Phytophthora root diseases (*Phytophthora* spp.)	White mottled rot (*Ganoderma applanatum*)
Northern Region (R1)	X	X	X		X	X		
Rocky Mountain Region (R2)	X	X		X	X	X		X
Southwestern Region (R3)	X	X			X			X
Intermountain Region (R4)	X	X			X	X		
Pacific Southwest Region (R5)	X	X		X	X		X	
Pacific Northwest Region (R6)	X	X	X	X	X		X	
Southern Region (R8)		X			X	X	X	
Northeastern Area (R9)	X	X		X	X	X		X
Alaska Region (R10)	X	X				X		

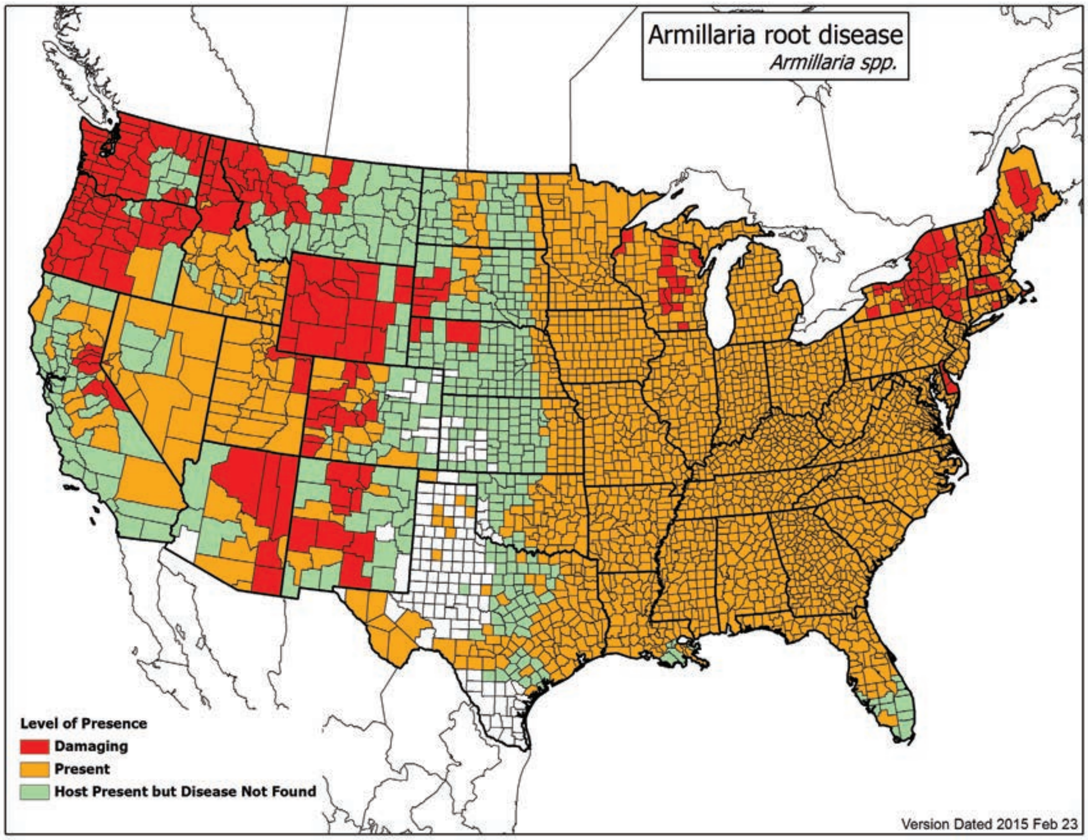

Figure 13—Distribution of hosts and damage caused by Armillaria root disease (*Armillaria* spp.) at the county level across the contiguous United States. In green counties, the hosts are present, but the specific root disease has not yet been detected although not all areas have been surveyed. In orange counties, both the tree hosts and the root disease are present. In red counties, the root disease is considered damaging in multiple forest stands to such an extent that management is affected.

Dessur., *A. sinapina* Bérubé & Dessur., *A. gallica* Marxmüller & Romagn., *A. gemina* Bérubé & Dessur., *A. tabescens* (Scop.) Emel, and *A. altimontana* Brazee, B. Ortiz, Banik, & D.L. Lindner (formerly NABS X) cause root disease throughout the United States. These *Armillaria* species affect most of the important tree species in the Northeastern Area (Blodgett and Worrall 1992; Brazee and Wick 2009). The main cause of Armillaria root disease in western conifers is *A. ostoyae*, whereas the other *Armillaria* species tend to be less pathogenic or only saprophytic (Filip et al., in preparation; Shaw and Kile 1991). However, *A. mellea* is a significant pathogen on hardwoods in California (Baumgartner and Rizzo 2001), and *A. sinapina* and *A. gallica* are thought to be the main cause of root disease in hardwoods in Wyoming and South Dakota (Blodgett 2015; Blodgett and Lundquist 2011).

Armillaria species can persist on a site for decades in the coarse roots of infected trees (Redfern and Filip 1991). One *A. ostoyae* clone in Oregon is causing disease on nearly 2,400 acres (970 ha) and has been estimated to be at least 1,900 years old (Ferguson et al. 2003). Once established on a root of a living host, the fungus invades and kills the cambium of the root and then decays the root tissues, which compromises the absorption of water and nutrients, causing direct mortality or greater susceptibility to stem failure and attack by insects and other pathogens (Baumgartner et al. 2011; Shaw and Kile 1991). Spread occurs when the fungus moves from an infected root system to neighboring trees by root-to-root contact, or by limited growth of rhizomorphs through the soil. Rhizomorphs are root-like structures (fig. 14) that are able to grow through the upper soil layers for several feet and directly infect tree roots. The reproductive structures of *Armillaria* species are mushrooms (fig. 15), the spores of which appear to play a limited role in spreading the disease (Baumgartner et al. 2011).

Occurrence

Pathogenic species of *Armillaria* are distributed throughout most of the forested regions of the continental United States, Alaska, and Hawaii; however, the impacts they have on forest ecosystem services vary greatly by species of *Armillaria*, host, and site. In the Northeastern Area, the primary hosts are species of oak, maple, beech, birch, aspen, balsam fir, spruce, and pine (see the appendix for tree species nomenclature). Armillaria root disease occurs throughout the Rocky Mountain Region and primary hosts include Douglas-fir, true firs, spruce, and lodgepole and ponderosa pines, and aspen, narrowleaf and plains cottonwoods, balsam poplar, bur oak, paper birch, green ash, and other hardwoods. Interior Douglas-fir and true firs are the most susceptible tree species in the Pacific Northwest and Northern Regions, but pine and other species may be highly susceptible on some sites, especially if the trees are maladapted to the site. In the Southwestern Region, interior Douglas-fir and Engelmann spruce sustain the most damage, but in some areas ponderosa pine is also a prominent host (Omdal et al. 2004). In Alaska and the Southern Region, *Armillaria* is not usually the primary cause of tree mortality, but is an opportunist on many tree species affected by other factors. In Hawaii, *Armillaria* species have been found associated with declining stands, but the overall incidence on the Hawaiian islands is unknown (Hanna et al. 2007; Kim et al. 2010).

Impacts

Armillaria root disease affects many forest products and services including recreation, timber, and aesthetics. Along with causing indirect tree mortality through snapping or uprooting, *Armillaria* causes direct tree mortality, growth reduction, and wood loss due to decay, and predisposes trees to other lethal agents. Mortality due to infection by *A. ostoyae* in the Northern Region is greatest on warm, moist habitats though large disease pockets also develop on dry sites and cold, high-elevation sites (Byler et al. 1990). Armillaria root disease is broadly distributed throughout much of the Intermountain Region but causes little direct mortality except in seedlings and saplings regenerating near infected stumps of the

Figure 14—Rhizomorphs of an *Armillaria* species (photo: J. O'Brien, U.S. Forest Service, Bugwood.org).

Figure 15—Mushrooms of *Armillaria ostoyae* (photo: B. Lockman, U.S. Forest Service).

previous generation; however, rot develops in the basal stem wood (butt) of mature trees in these areas (Hagle 2010). In the Pacific Northwest Region, disease is severe on grand fir, white fir, and interior Douglas-fir, and sometimes on pines and other species. Armillaria root disease is generally worse east of the Cascade Mountains and in southwestern Oregon but does cause high levels of damage on some harsh sites in western Oregon and Washington, especially in areas with compacted soils (Goheen and Willhite 2006). In the Southwestern and Intermountain Regions, Armillaria root disease is contributing to dieback and mortality in old-growth spruce and true fir forests, but causing only minor losses in younger forests except in areas with substantial soil disturbance. In the Rocky Mountain Region, a recent, systematic survey across forest types in Wyoming found *Armillaria* species causing disease in 22 percent of surveyed locations (J.T. Blodgett, U.S. Forest Service, Forest Health Protection, Rapid City, SD, pers. comm., March 5, 2015). In southeast Alaska, Armillaria root disease is a leading cause of heart rot of western hemlock and Sitka spruce.

Mortality from Armillaria root disease may occur in patches up to tens of acres in size or as scattered individual tree mortality (fig. 16). In the West, changes in forest tree species composition have resulted in an increase in species more susceptible to Armillaria root disease, such as interior Douglas-fir, subalpine fir, white fir, and grand fir (Filip et al. 2007; Filip et al., in preparation; Hagle et al. 1995, 2000). Tree species composition has changed primarily because of fire exclusion but also because of other factors including the introduction of *Cronartium ribicola* Fisch. (the cause of white pine blister rust). In northern Idaho and western Montana, long-term plots (Hagle 1985) and analyses indicate that Armillaria root disease infests more than 12 million acres (4.9 million ha), and almost 2.5 million of those acres (1 million ha) will have greater than 25-percent mortality of mature stems by 2027 (Krist et al. 2007). Damage is most severe on the best growing sites, and severely affected stands often convert to brush fields in the absence of tree species tolerant to Armillaria root disease. In Colorado, annual volume losses by *Armillaria* in subalpine fir have been estimated to be 370,800 ft^3 (10,500 m^3) (Allen et al. 2011; Fuller and Johnson 1985). In severely infested Pacific Northwest forests, tree mortality caused by *A. ostoyae* ranges from 25 to 50 ft^3 per acre per year (1.7 to 3.5 m^3 per ha per year) (Filip et al. 2010). In addition to tree mortality, *Armillaria* significantly affects tree growth and site productivity. Recent research has shown that many infected trees have greatly reduced growth with no aboveground symptoms (Bloomberg and Morrison 1989; Cruickshank 2011; Cruickshank et al. 2011).

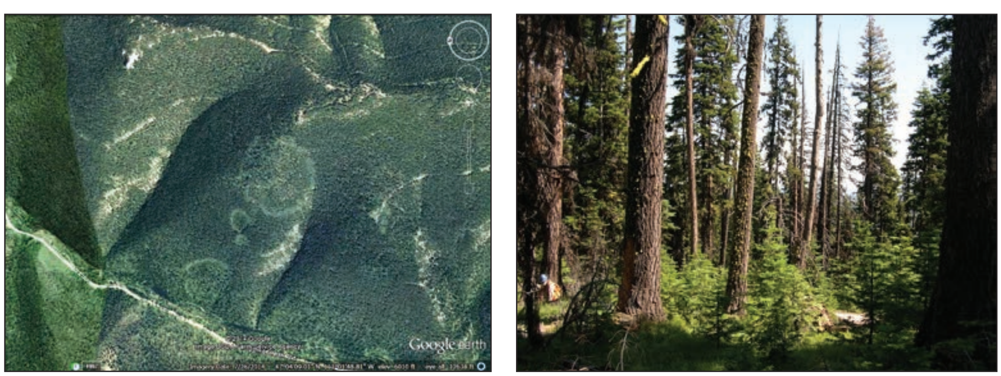

Figure 16—Distinct pockets of mortality from Armillaria root disease as seen from the air in central Montana (left) (Google™ Earth 2014) and on the ground in Oregon (right) (photo: G. Filip, U.S. Forest Service).

In the Northeastern Area, past mortality from Armillaria root disease most commonly occurred as scattered individual trees. More recently, impact from *Armillaria* appears to be increasing due to synergistic effects of exotic insects and diseases and extreme weather events including ice storms and severe drought. Although rarely quantified, in forest plantations *Armillaria* species can cause 3 to 50 percent mortality over a rotation (Wargo and Harrington 1991), and some of the most widely distributed species also frequently cause butt rot (Brazee and Wick 2009). Detrimental impacts of many *Armillaria* species are often associated with environmental stresses, such as drought and late spring frost (Wargo 1996). In the Northeastern Area where turkey (*Meleagris gallopavo*), deer (*Odocoileus* spp.), and bear (*Ursus* spp.) populations are highly dependent on oaks and beech, Armillaria root disease often results in mast reduction and loss of the oak type.

Armillaria root disease predisposes trees to insects (Bartos and Schmitz 1998; Fuller 1983; Goheen and Hansen 1993; Hertert et al. 1975; Kulhavy et al. 1984; Tkacz and Schmitz 1986) and other diseases (Filip et al., in preparation). During periods between bark beetle epidemics, trees affected by root disease foster endemic beetle populations. In the Front Range of Colorado and the Black Hills of South Dakota, 62 percent and 75 percent of ponderosa pine attacked by mountain pine beetle, respectively, were also infected by Armillaria root disease (Fuller 1983). In the Northeastern Area, *Armillaria* species are associated with several native and exotic insect defoliators. For example, losses of oak trees attacked by *Armillaria* species after defoliation by the exotic gypsy moth have been reported throughout the Northeast. *Armillaria* species have also been associated with native defoliating insects of oaks and maples (Wargo 1996) and partial cuttings and disturbance (Wargo and Harrington 1991). Considering this association with environmental stress, insect defoliators, and disturbance, one would expect *Armillaria*-related mortality to increase due to severe storms, insect defoliator outbreaks, and fragmented landscapes. Under a changing climate, the incidence of and impact from Armillaria root disease are expected to increase. If growing conditions also become drier, then the impact from Armillaria root disease will be even greater due to the increased stress on the host trees (Kliejunas 2011; Kliejunas et al. 2009; Klopfenstein et al. 2009). Armillaria root disease is also a common contributing factor in many forest declines such as oak decline (Kile et al. 1991; Wargo and Harrington 1991).

Armillaria also has a large but unmeasured impact on recreation sites (Filip et al., in preparation). Live trees often fall due to mechanical failure resulting from root decay, which is a major safety concern in these sites. Armillaria root disease is a concern in all hazard tree mitigation efforts in developed sites. It is also an important consideration in vegetation restoration projects where susceptible hosts are a significant component.

Management

The primary focus for management of Armillaria root disease is observing which species on the site appear to be tolerant or resistant and favoring those species during thinning and regeneration (Filip et al. 2010; Filip et al., in preparation; Hadfield et al. 1986; Hagle and Shaw 1991; McDonald et al. 2005; Rippy et al. 2005; Shaw et al. 2009). Prevention of soil compaction and tree wounding during management activities is encouraged. Where groups of infected trees, or disease centers, are recognized, these centers can be managed differently from uninfected areas around the centers. The removal of infected stumps during regeneration may significantly reduce root disease in the future stand (Hagle and Shaw 1991; Morrison et al. 2014), but this approach has not been widely implemented in the United

States. Initial trials of biological control agents for Armillaria root disease are promising and warrant further investigation (Chapman et al. 2004).

Heterobasidion Root Disease
Heterobasidion Species

Biology and Ecology

Heterobasidion root disease (fig. 17) in North America is caused by the fungi *Heterobasidion irregulare* Garbelotto & Otrosina and *H. occidentale* Otrosina & Garbelotto. Most coniferous species (and a few hardwoods) are susceptible to infection by *Heterobasidion* species, although the two species have distinct host specificities. In general, *H. irregulare* infects pine species, whereas *H. occidentale* infects other species (Otrosina and Garbelotto 2010). Both species produce perennial fruiting structures (sporophores or conks) that release wind-disseminated spores (Asiegbu et al. 2005; Hodges 1969; Hsiang et al. 1989) (fig. 18). Infections caused by *H. irregulare* spores are usually limited to the tops of freshly cut stumps in pine species (Otrosina and Cobb 1989), whereas *H. occidentale* spores readily infect freshly cut stumps and fresh stem wounds in other species (Otrosina and Garbelotto 2010). *Heterobasidion* species in the newly infected stump or tree may then infect a neighboring tree via root-to-root contact, leading to the development of disease

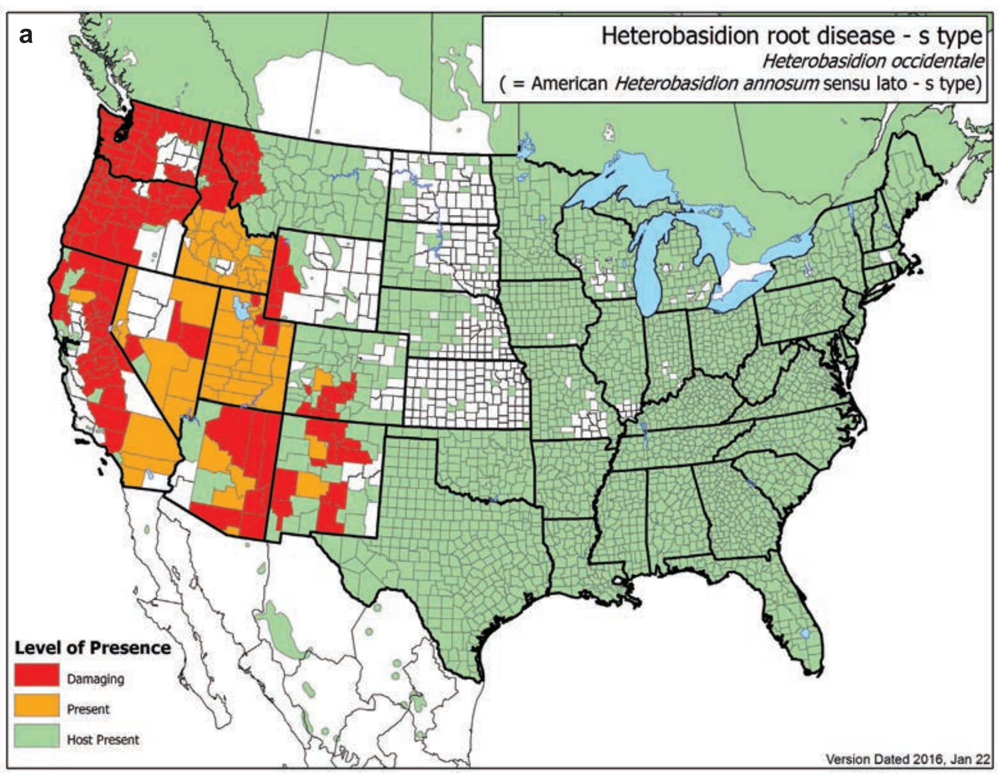

Figure 17—Distribution of hosts and damage caused by Heterobasidion root disease, (a) *Heterobasidion occidentale* and (b) *H. irregulare*, at the county level across the contiguous United States. In green counties, the hosts are present, but the specific root disease has not yet been detected although not all areas have been surveyed. In orange counties, both the tree hosts and the root disease are present. In red counties, the root disease is considered damaging in multiple forest stands to such an extent that management is affected.

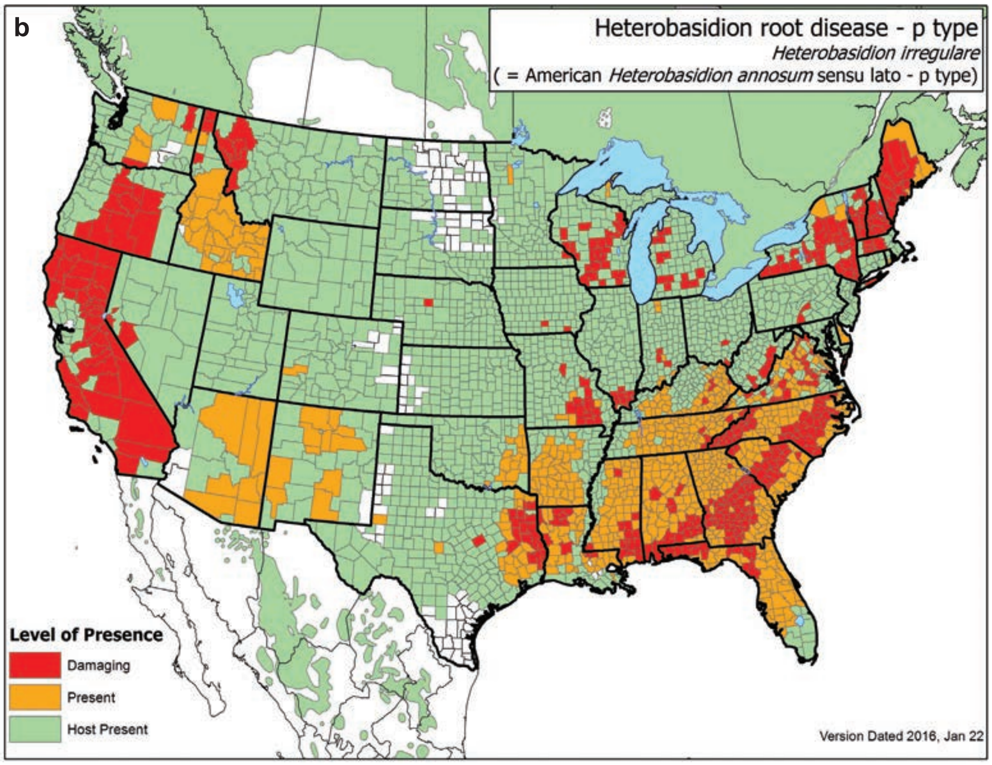

Figure 17—(Continued).

Figure 18—*Heterobasidion* fruiting structures in a fir stump (photo: H. Kearns, U.S. Forest Service).

Figure 19—Pockets of mortality due to Heterobasidion root disease in planted pine near Nacogdoches, TX. (photo: G. Mason, U.S. Forest Service, Bugwood.org).

centers (fig. 19). Although both species have been isolated from "nonhost" stumps without causing disease in neighboring "host" trees (Kliejunas 1986; Lockman 1993; Otrosina et al. 1992), interior Douglas-fir and true firs are occasionally infected when growing near infected pine stumps.

Occurrence

Heterobasidion species exist across the continental United States and Alaska, but their impacts and the host species affected differ by region. In the Southern Region, Heterobasidion root disease affects all pines but has the greatest impact on the commercial species including loblolly, slash, shortleaf, and longleaf pines. In the Northeastern Area, Heterobasidion root disease has been found causing damage in one county in Minnesota, and is widespread in Wisconsin and Michigan, where it is most damaging to red and jack pines after thinning (Stanosz et al. 1995; Wisconsin Department of Natural Resources 2003), especially on sandy sites. True firs, interior Douglas-fir, and ponderosa pine are the most susceptible and affected species in the Northern Region; true firs, hemlocks, and ponderosa pine are the most affected species in the Pacific Northwest Region. Across the Pacific Southwest Region, *Heterobasidion* species are widespread and can be found on nearly every coniferous species (Bega and Smith 1966; Schmitt et al. 2000; Smith 1989), although true firs, ponderosa pine, and Jeffrey pine are the most severely affected trees. In the Intermountain Region, *Heterobasidion* species can be found on every coniferous species except limber pine, whitebark pine, and western larch (Tegethoff 1973), and *H. occidentale* is common in subalpine fir stands in high-elevation areas. In the Rocky Mountain Region, *H. occidentale* is common in forests with white fir (Worrall et al. 2010). In coastal Alaska, low-level impacts from Heterobasidion root disease are reported in young stands of hemlock and Sitka spruce, and in old-growth timber in southeast Alaska.

Creation of stumps from harvesting provides entry courts for the spores of *Heterobasidion* species, favoring development of the disease (fig. 20). In one survey on the Fremont National Forest in southern Oregon, true fir stands with multiple harvest entries had a 100-percent incidence of Heterobasidion root disease, compared to 12 percent of stands with no history of harvesting (Goheen and Goheen 1989). In the Southern Region, soil texture is an important factor in the severity of the disease (Alexander et al. 1975); soils at high risk for Heterobasidion root disease are characterized as sand, sandy loam, or loamy sand deeper than 10 inches (25 cm), with a low water table (Morris and Frazier 1966). It is thought that well-drained, sandy soils increase potential drought stress of the host, which may favor subsequent growth of the pathogen in the roots (Towers and Stambaugh 1968). Sandy soils also allow for increased root connections (Kuhlman 1974) and foster the ability of spores to percolate through the soil and infect roots directly (Kuhlman 1969). In the Northeastern Area, Heterobasidion root disease is widespread in New York south of the Adirondack Mountains but is severe only in pine plantations on sandy sites in the eastern and southeastern part of the state. Plantations on former agricultural sites may sustain more damage than those on continuously forested sites.

Figure 20—Mortality around stump infected with Heterobasidion root disease (photo: G. Filip, U.S. Forest Service).

Impacts

Root and butt rot caused by *Heterobasidion* species progresses from resin-soaked and stained wood, to a white pocket rot or white stringy rot. Trees affected by Heterobasidion root disease often appear healthy until more than half the roots, or the majority of the root collar, are infected. Trees with Heterobasidion root disease often become windthrown or are attacked by bark beetles prior to crown symptoms of decline (Schmitt et al. 2000; Sinclair and Lyon 2005).

Heterobasidion root disease can reduce tree growth and subsequently increase host susceptibility to bark beetle attack (Alexander 1989; Ferrell and Smith 1976; Wisconsin Department of Natural Resources 2003). Radial growth losses of southern pines have been documented to range from 6 to 36 percent; height growth was reduced by 40 percent in trees with greater than 50-percent colonization (Alexander 1989). Trees stressed by Heterobasidion root disease are often attacked by bark beetles such as *Ips* species, *Scolytus* species*,* and *Dendroctonus terebrans* Olivier (Barnard 1999; Ferrell and Smith 1976; Livingston et al. 1983; Morris 1970). This root disease can also play a major role in southern pine beetle attack (*Dendroctonus frontalis* Zimmermann) (Alexander et al. 1980, 1981).

Heterobasidion root disease causes serious economic loss by way of mortality, growth loss, and the necessity of early harvest of a lower value product. In the Southern Region, the NIDFRA model (Krist et al. 2014) indicates that 38 million acres (15.4 million ha) of loblolly-slash-shortleaf pine forest are at risk of some level of loss from Heterobasidion root disease, with more than 3.3 million acres (1.3 million ha) expected to lose at least 15 percent of pine basal area in the next 15 years. More than 380,000 acres (153,800 ha) of eastern white pine are at some level of risk, with 167,000 of those acres (67,600 ha) expected to lose at least 25 percent of the host basal area over 15 years. The value of timber products harvested in the Southern Region in 2007 was estimated at $12 billion (Hanson et al. 2010) with softwood accounting for about 69 percent of these products (Wear et al. 2007). The monetary losses from Heterobasidion root disease in the Southeast are in the millions of dollars per year.

In several forested areas of eastern Oregon, 30 percent of pine stands are estimated to be infested by Heterobasidion root disease; infested stands support only 77 percent of the stocking and 44 percent of the basal area when compared to uninfested stands (Goheen and Goheen 1989). Heterobasidion root disease in true fir stands east of the Cascade Mountains has increased significantly due to the creation of large stumps from selective harvesting. In the Northern Region, an estimated 4 million acres (1.6 million ha) are affected by *H. occidentale*. Greater than 25-percent mortality over 15 years is expected on more than 770,000 of those acres (311,600 ha) (S.K. Hagle, unpublished data).[2] Another 114,000 acres (46,100 ha) of ponderosa pine are affected by *H. irregulare* in western Montana (B. Lockman, unpublished data).[2]

In the Rocky Mountain and Southwestern Regions, few data are available for *Heterobasidion* species, but frequency is thought to be low for both species (Worrall et al. 2010). In the Southwestern Region, annual mortality rates were estimated at 1 percent in the pine type, 9 percent in mixed-conifer forests, and 14 percent in spruce-fir forests (Wood 1983); however, rates are increasing in the wake of selective harvesting, aging stands, and drought. In contrast, it is thought that lack of large-tree harvesting coupled with extensive stand-replacing fires has led to a significant reduction of *H. irregulare* in southern Idaho (J.T. Hoffman, personal communication, May 31, 2011). In the Pacific Southwest Region, Heterobasidion root disease is estimated to infect approximately 12.5 percent of the State's 16 million acres (6.5 million ha) of commercial forest land, resulting in annual losses of about 222 million board feet (MMBF) (18.5 million ft^3, 524,000 m^3) (California Forest Pest Council 1988). This equates to an annual loss approaching $50 million (July 2014–December 2014 average stumpage values for ponderosa pine; California State Board of Equalization 2014). In southeast Alaska, a *Heterobasidion* species is one of three fungi contributing to a one-third volume loss in old-growth timber (Filip and Morrison 1998).

[2] Data on file with B. Lockman, U.S. Forest Service, Forest Health Protection, Missoula, MT.

Heterobasidion root disease is also a threat to visitor safety and property in the form of hazard trees on public lands (Filip and Goheen 1982a; Marosy and Parmeter 1989). National forests across the nation have an estimated annual visitation rate of more than 173 million people (U.S. Forest Service 2010). Tree failures from root disease are a great concern; for all entries into the International Tree Failure Database through July 2010, 35.2 percent of tree failures were due to root failures (International Tree Failure Database 2010). Although actual injury and property loss from hazard trees are infrequent, managers of recreation sites are likely to be held liable and sued for compensation (Anderson 1988).

Heterobasidion root disease also affects carbon sequestration. The southeastern forests are estimated to sequester 100 million metric tons of carbon dioxide per year, or a third of U.S. forests' capacity to absorb carbon dioxide (Jose 2007). Losses to Heterobasidion root disease are estimated to be greater than 15 percent of the 2012 host basal area on 3.6 million acres (1.5 million ha) by 2027 (Krist et al. 2014). And, as the climate changes, losses from Heterobasidion root disease are expected to increase (Kliejunas et al. 2009; Nilson et al. 1999). In the Southern Region, infected stands will probably be harvested prematurely, altering carbon sequestration for years. These areas could also be converted to a land use other than forestry that is seen as more profitable, which may greatly reduce future carbon sequestration.

Management

Preventing the introduction of the disease onto a site is the best method available for reducing the impact from *Heterobasidion* species in forests. This approach is especially applicable in pine stands, where stem wounds are less likely to become a site for infection than in species with thinner bark. Establishment of *Heterobasidion* from spores can be prevented by using stump treatments, which is the primary method to prevent Heterobasidion root disease (Asiegbu et al. 2005). Treatments to prevent stump infection include two borate salts: sodium tetraborate decahydrate (Sporax™) and disodium octaborate tetrahydrate (Cellu-Treat™).[3] Registrations for these products are necessary for use, but such registrations are dependent on the financial feasibility to the producers. As of this writing, the registration for Sporax, the most commonly used stump treatment in the United States, is scheduled to be discontinued due to the high cost of maintaining its registration. Local strains of the fungus *Phlebiopsis gigantea* (Fr.) Jülich are currently being tested for the control of Heterobasidion root disease in the Southern Region. Additional work is necessary to get this product labeled for use in the United States.

Silvicultural techniques are also available for minimizing the impacts from this disease, such as minimizing wounds to residual trees, converting a site to tree species more tolerant to Heterobasidion root disease, and managing density to decrease root contacts and improve drought tolerance of residual trees (Alexander 1989; Asiegbu et al. 2005; Rippy et al. 2005). In the Southern Region, new pine stands are planted on a wide spacing (200 to

[3] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

400 trees per acre, 494 to 988 trees per ha) to delay thinning and thus reduce future infections (Alexander 1989). Wide spacing also decreases the potential for root-to-root contact, thus decreasing the spread potential if the fungus does enter the stand. Minimizing wounding of residual trees is highly recommended in the Pacific Northwest (Hadfield et al. 1986; Petersen 1989; Rippy et al. 2005), especially in thin-barked species, such as hemlock and true fir (Russell 1989). Wounds are considered the main point of entry in these thin-barked species.

Although expensive and not widely used, removal of stumps is a method that has been applied to high-value sites such as seed orchards (Alexander 1989). In recreation areas that have large numbers of affected trees, it may be necessary to close a site permanently or at least until the susceptible overstory is removed (West 1989).

Laminated Root Rot
Phellinus sulphurascens Pilát (formerly *P. weirii* (Murrill) Gilb. Douglas-fir Form)

Biology and Ecology

Phellinus sulphurascens Pilát (formerly *P. weirii* (Murrill) Gilb. Douglas-fir form) causes laminated root rot (fig. 21), which affects Douglas-fir and other commercially important conifer species in the northwestern United States. *Phellinus sulphurascens* is a fungus that produces a mostly annual, crust-like fruiting structure, or sporophore. Spores are dispersed by wind or water, occasionally landing on a substrate that is suitable for their survival

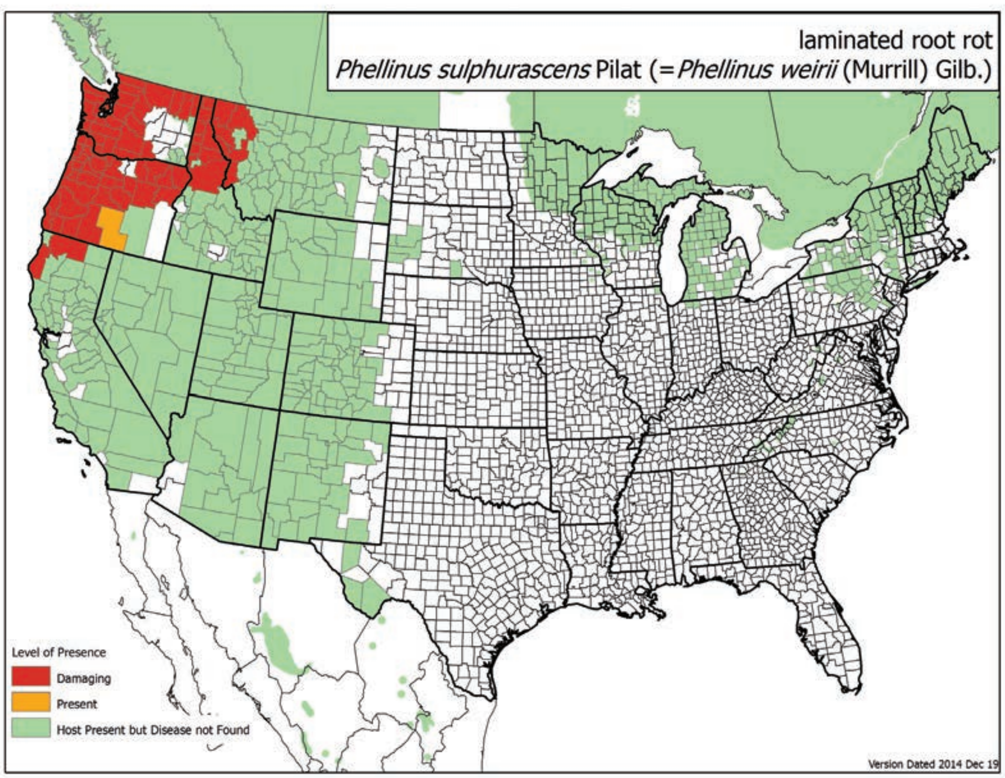

Figure 21—Distribution of hosts and damage caused by laminated root rot (*Phellinus sulphurascens*) at the county level across the contiguous United States. In green counties, the hosts are present, but the specific root disease has not yet been detected although not all areas have been surveyed. In orange counties, both the tree hosts and the root disease are present. In red counties, the root disease is considered damaging in multiple forest stands to such an extent that management is affected.

(Nelson 1976). The mycelium that grows from a germinated spore must establish on suitable wood and then outcompete other fungi in order to survive. Once established, it spreads from woody substrates to the roots of live trees through direct root contact with infested wood. The fungus invades and kills the cambium of the root and then decays the dead root tissues. It may eventually travel up the root to colonize the root collar, and girdle the tree.

Many conifers in the northwestern United States are occasionally infected, but Douglas-fir, mountain hemlock, grand fir, and white fir are the most susceptible species in the Pacific Northwest Region (Hadfield and Goheen 1986; Hansen and Goheen 2000). In the Northern Region, Douglas-fir and grand fir are the most common hosts, with subalpine fir commonly infected when growing in proximity to grand fir (Thies and Sturrock 1995).

Laminated root rot is a "disease of the site"; established mycelia of this fungus are essentially permanent on a site (Thies and Sturrock 1995). The fungus spreads underground through tree root systems and survives for many decades in dead roots and stumps. *Phellinus sulphurascens* kills trees in expanding patches that can be from a few trees to many acres in size (fig. 22). These patches may be dispersed throughout a stand. Trees of all ages are killed as their roots are destroyed by the fungus. Many also die from windthrow following decay of support roots.

Figure 22—Large, expanding mortality pocket from laminated root rot (*Phellinus sulphurascens*) in northwestern Montana (photo: B. Lockman, U.S. Forest Service).

Occurrence

Laminated root rot is best known and probably most damaging in coastal Douglas-fir forests of the Pacific Northwest Region. Surveys indicate that nearly 9 percent of the Douglas-fir forest area in western Oregon is occupied by laminated root rot centers in which half of the Douglas-firs have been killed (Hansen and Goheen 2000). In interior Pacific Northwest forests, laminated root rot can cause severe damage where Douglas-fir and true fir exist. It is also a major disease in forests of the Northern Region, where it causes problems on a narrow range of habitats; cool, moist habitats typified by western hemlock and warm, moist grand fir habitat types make up most of the infested sites. Byler et al. (1990) found sites on the Lolo National Forest in western Montana on western hemlock habitat type to have far higher probability of laminated root rot than other habitat types.

Impacts

Significant amounts of decay can occur in root systems before trees infected with laminated root rot begin showing obvious crown symptoms (fig. 23). Slowed growth is usually the first observable symptom with cumulative growth loss dependent on the age of the tree. Diameter growth is more affected by laminated root rot than is height growth in coastal Douglas-fir (Harrington and Thies 2007; Thies 1983). Bloomberg and Wallis (1979) detected reduced radial increment in infected trees lasting 30 years or more before death in mature Douglas-fir; smaller trees had shorter periods of growth decline before death. The largest declines in growth occur in trees with the highest rates of decay (Harrington and Thies 2007).

Figure 23—Extensive decay from laminated root rot (*Phellinus sulphurascens*) in roots of live Douglas-fir (photo: G. Filip, U.S. Forest Service).

Laminated root rot is especially damaging if susceptible hosts are regenerated in areas where the disease was already present in previous stands.

In coastal forests, grand fir is the most susceptible species, followed by Douglas-fir. Nelson and Sturrock (1993) measured grand fir mortality rates averaging about 31 percent in 17 to 20 years for trees planted around infected stumps in coastal Oregon and British Columbia. Rates for coastal Douglas-fir averaged about 26 percent. Filip and Schmitt (1979) found mortality rates of 20 percent in Douglas-fir (mostly coastal variety) and 23 percent in grand fir. Similar rates of mortality were measured in the Northern Region on randomly placed plots, although interior Douglas-fir had a higher mortality rate than grand fir. A net loss in basal area of 35 percent for Douglas-fir and 20 percent for grand fir was measured. Monitored trees were at least 5 inches (12.7 cm) diameter at breast height at the start of the study and were followed over a 20-year period (S.K. Hagle, unpublished data).

In the Northern Region, it is estimated that nearly 740,000 acres (299,500 ha) are infested with *P. sulphurascens*. Of these, more than 150,000 acres (60,700 ha) have mortality rates of at least 25 percent of the basal area every 15 years. Large canopy gaps with over 75-percent canopy loss caused by laminated root rot are estimated to occupy more than 15,000 acres (6,100 ha) of the most productive forest land types in the Northern Region (S.K. Hagle, unpublished data). Douglas-fir and grand fir forests on warm, moist site types are damaged the most (Byler et al. 1990). Estimates of area occupied by laminated root rot in the Pacific Northwest Region vary from 5 to 11 percent of Douglas-fir forests, and the annual volume lost is estimated to range from 32 million to 83 million ft^3 (906,000 to 2.4 million m^3) (Washington State Academy of Sciences 2013).

Laminated root rot significantly affects developed sites throughout its range, and is considered the most serious root disease affecting developed-recreation sites in the Pacific Northwest Region (Filip and Goheen 1982a). Campgrounds have been closed due to the hazards represented by *P. sulphurascens* (K.L. Chadwick, personal communication, February 27, 2013).

In contrast with the negative impacts that *P. sulphurascens* has on forest stands, its presence can lead to an increase in plant community diversity. Laminated root rot is a major factor in shaping forest structure, composition, and processes, such as successional trajectories, wherever it occurs (Hansen and Goheen 2000).

Impacts from root diseases potentially could increase under current climate change scenarios due to the expected increased stress of their host trees (Woods et al. 2010). The incidence and spread of *P. sulphurascens* is not tied to host stress, but is more dependent on the distribution of the hosts, which may be affected by climate change (Hansen and Goheen 2000).

Management

Methods for managing laminated root rot fall into two general categories: silvicultural control of the disease and removal or reduction of the inoculum (infected substrate wood material) (Hadfield et al. 1986; Rippy et al. 2005; Thies and Sturrock 1995). Silvicultural control includes planting and managing for tree species tolerant to laminated root rot in an approach called species conversion. The easiest time to accomplish this is at the final harvest, when an infected stand can be regenerated to more tolerant species. Favoring tolerant species during any intermediate entry into an infected stand can also be used to decrease losses to laminated root rot as well as reduce the inoculum on the site. Wide spacing of young stands is another method of controlling disease within an infested stand. Wide spacing (more than 13 feet, 4 meters, between trees) reduces root contacts between trees, which in turn reduces the spread of the fungus through the root systems. This method should be used with great caution, as periodic entries are required to remove natural regeneration, but the method is appropriate for Douglas-fir age 60 years or less growing on deep soils (Thies and Sturrock 1995).

Removal or reduction of inoculum can be accomplished by stump removal and push-over logging (Hadfield et al. 1986; Thies and Sturrock 1995). Both techniques remove the majority of infected root systems from the site, thus removing the inoculum and greatly reducing carryover of the disease into the next generation of trees. Inoculum removal or reduction allows managers to grow Douglas-fir on high-value sites infested with laminated root rot. Both techniques can cause extensive disturbance on a site with mixed effects on growth of the subsequent stand (Morrison et al. 2014; Zabowski et al. 2008).

Inoculum reduction by the use of biological control agents antagonistic to *P. sulphurascens* is a possibility, but a suitable biological control agent has yet to be found (Thies and Sturrock 1995). Use of chloropicrin for chemical reduction of inoculum in stumps has been tested with no detectable decrease in replacement-stand mortality resulting from laminated root rot (Thies and Westlind 2006).

Black Stain and Related Root Diseases *Leptographium* Species

Biology and Ecology

Several species of *Leptographium* are associated with root diseases of conifers in the United States. In the western United States, black stain root disease (BSRD) (fig. 24), a wilt-like disease of conifers caused by the native, insect-vectored, fungal pathogen *Leptographium wageneri* (Kendr.) Wingf. (Harrington and Cobb 1983, 1988), is considered the most important. In terms of pathogenesis, BSRD diverges from typical root diseases by neither causing wood decay nor invading the cambium prior to tree death (Cobb 1988). *Leptographium wageneri* is commonly found in ponderosa, lodgepole, and Jeffrey pines (var. *ponderosum* Harrington & Cobb); Douglas-fir (var. *pseudotsugae* Harrington & Cobb); and pinyon and singleleaf pinyon pines (var. *wageneri* (Kendr.) Wingf.). It is considered one of the five most damaging root diseases in western forests (Hadfield et al. 1986) and is widespread across much of the range of its hosts, but incidence and severity, and thus the importance to forest management, vary greatly (Ferguson 2009). Because *L. wageneri* is an insect-vectored pathogen and the vectors are generally attracted to weakened trees, this fungus often occurs in complexes with other root disease fungi (Filip and Goheen 1982b; Goheen and Filip 1980; Morrison and Hunt 1988). It has been found colonizing the same roots of Douglas-fir as *Armillaria ostoyae* (Byler et al. 1983; Goheen and Hansen 1978; Morrison and Hunt 1988), *Phellinus sulphurascens* (Filip and Goheen 1982b; Goheen and Filip 1980; Morrison and Hunt 1988; Witcosky 1989), and a *Heterobasidion* species (Kelsey et al. 1998).

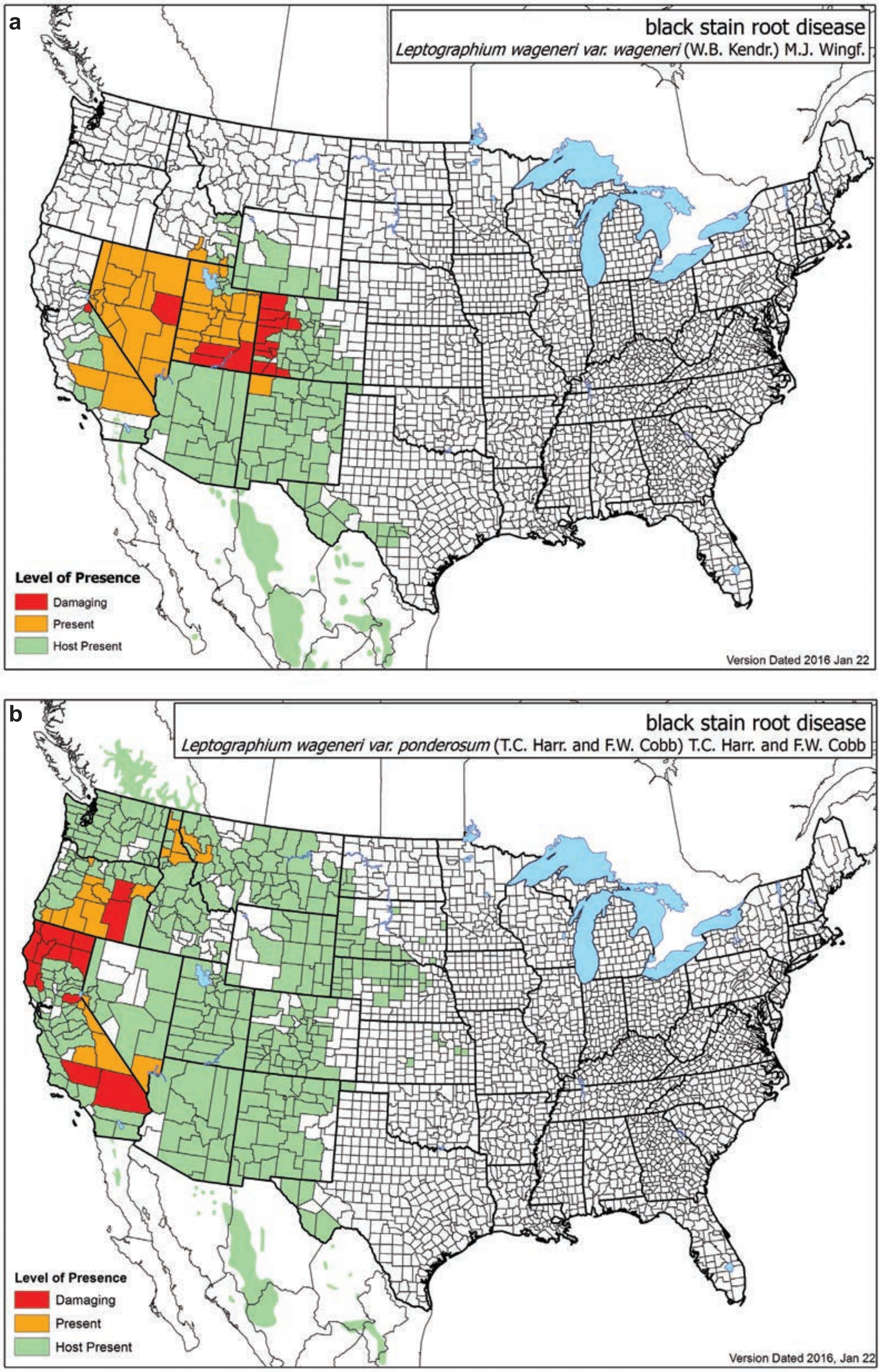

Figure 24—Distribution of hosts and damage caused by black stain root disease (a, b, and c: three varieties of *Leptographium wageneri*) at the county level across the contiguous United States. In green counties, the hosts are present, but the specific root disease has not yet been detected although not all areas have been surveyed. In orange counties, both the tree hosts and the root disease are present. In red counties, the root disease is considered damaging in multiple forest stands to such an extent that management is affected.

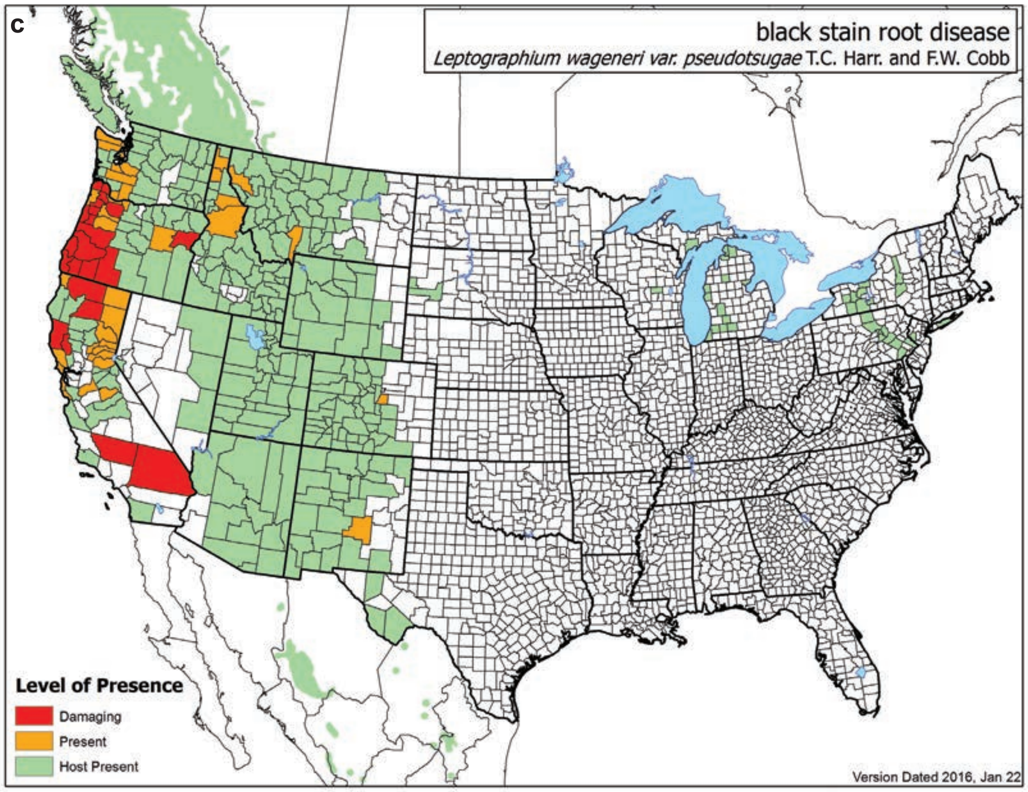

Figure 24—(Continued).

In the eastern United States, two other species of *Leptographium* cause damage, *L. procerum* (Kendr.) Wingf. and *L. terebrantis* Barras & Perry. Both species are associated with red pine decline in the Lakes States. Red pine decline is caused by a complex of interacting organisms in which both *L. procerum* and *L. terebrantis* are considered weakly pathogenic and consistently work in concert with insects. Among these insects are root collar weevil (*Hylobius radicis* Buchanan), pales weevil (*H. pales* Herbst), red turpentine beetle (*Dendroctonus valens* LeConte), pitch-eating weevil (*Pachylobius picivorus* Germar), and *Hylastes porculus* Erichson, which feed on freshly cut stumps and the lower stems and roots of red pine and carry the fungi into the lower stem and root system (Erbilgin and Raffa 2002; Klepzig et al. 1991). Bark beetles (*Ips pini* Say and *I. grandicollis* Eichhoff) are ultimately responsible for the tree's death (Erbilgin and Raffa 2002; Klepzig et al. 1991). *Leptographium terebrantis* is also present in the Rocky Mountain Region and has caused significant damage in some stands (Blodgett 2013; Holah 1993).

Leptographium procerum is the causal agent of procerum root disease, which results in root lesions, basal cankers, and occasionally death of pine species, especially young (less than 20-year-old) eastern white pine. Procerum root disease is often associated with pines stressed by poor sites, weevil infestations of the major roots and root collar, and other root pathogens (Alexander et al. 1988; Sinclair and Lyon 2005). Once established in a pine plantation with interconnected root systems, *Leptographium* species can spread to healthy trees through root connections. The wood of colonized roots is resin soaked, and the infected trees become stressed because they have reduced capacity to absorb and move water and synthesize defensive compounds (fig. 25). These stressed trees continue to attract beetles that feed on the lower stem, particularly the red turpentine beetle (Erbilgin and Raffa 2002; Klepzig et al. 1991).

Figure 25—Characteristic staining of the water-conducting tissue in the sapwood of a pine with black stain root disease (*Leptographium wageneri* var. *wageneri*) (photo: W. Jacobi, Colorado State University, Bugwood.org).

Occurrence

Although *Leptographium wageneri* can be found throughout northern Idaho and Montana, BSRD is generally observed only in conjunction with other root pathogens considered to be the primary agent of mortality (Byler et al. 1983), or in offsite ponderosa pine plantations (Ferguson 2009). This disease is present throughout the range of pinyon pine in western Colorado, where it is generally found on the more productive pinyon sites (Landis and Helburg 1976). A 1998 ground survey in southwestern Colorado found an estimated 2 to 4 percent of pinyon pine were infected (W.R. Jacobi, unpublished data)[4] (fig. 26). In Nevada, Utah, and southern Idaho, BSRD is found on just over 3,000 acres (1,200 ha) of pinyon pine stands used for Christmas tree production (J. Guyon, personal communication, April 24, 2011), where it is often most apparent at the beginning of a period of drought. In the central Sierra Nevada Mountains, a high proportion of the largest and most active infection sites in ponderosa pine occur in moist, cool areas, and spread of the pathogen appears to be more rapid in gullies and small creek drainages (Wilks et al. 1985).

Figure 26—Black stain root disease center (*Leptographium wageneri* var. *wageneri*) in pinyon pine, southwestern Colorado (photo: H. Kearns, U.S. Forest Service).

[4] Data on file with W.R. Jacobi, Professor Emeritus, Colorado State University, Department of Bioagricultural Sciences and Pest Management, Fort Collins, CO.

In Washington, Oregon, and northern California the disease is most commonly found in 10- to 30-year-old Douglas-fir plantations and dense natural regeneration west of the Cascade Crest and in ponderosa pine of all ages east of the Cascade Mountains. In southwestern Oregon, BSRD was detected in 19 percent of five hundred 10- to 30-year-old Douglas-fir plantations, compared to 1 percent with Armillaria root disease and 7 percent with laminated root rot (Hessburg et al. 2001). Approximately 80 percent of mortality centers in Douglas-fir are associated with disturbed areas: road edges, clear-cut margins, thinnings, areas with drainage problems, and places where previous soil disturbance such as compaction and displacement have occurred (Goheen and Hansen 1978; Hansen 1978). To date there has been no systematic effort to map *L. wageneri* in the western United States, but historical records of *L. wageneri* have been cataloged in the California Insect and Disease Atlas (CAIDA) database (CAIDA 2014) (fig. 27).

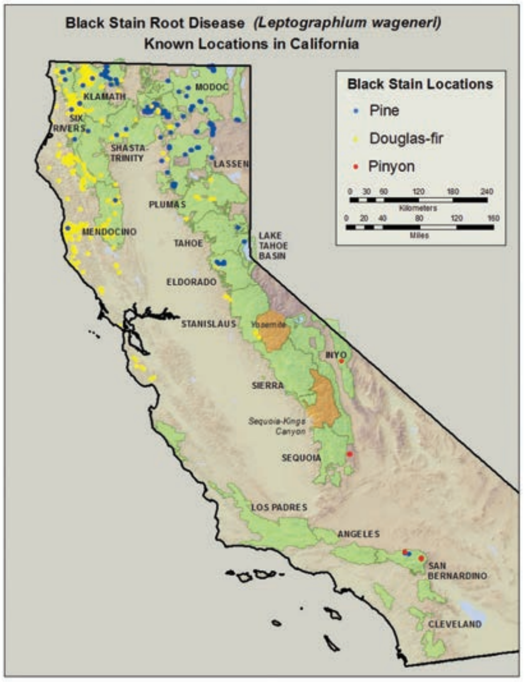

Figure 27—Historical records of black stain root disease (*Leptographium wageneri*) in California Insect and Disease Atlas (CAIDA May 2014).

In the eastern United States, procerum root disease causes mortality and growth losses in eastern white pine and red pine primarily in young pine and Christmas tree plantations. In the Northeastern Area, root diseases caused by *Leptographium* species occur mainly in the Lake States, often in red pine planted on lower quality pin oak sites, where the root diseases are associated with red pine decline. In the Southeast, the species play a role in the decline of pines damaged by various causes.

Impacts

In the Northeastern Area, *Leptographium* infections in red pine and eastern white pine result in mortality and growth losses, with mortality between 20 and 50 percent in some plantations (Sinclair and Lyon 2005). Live pinyon pine density in discrete, recently formed BSRD mortality centers in southwestern Colorado was reduced by an average of 63 percent, and 76 percent of pinyon in these centers were infected by *L. wageneri* (Kearns and Jacobi 2005). In Oregon, Washington, and northern California, *L. wageneri* is considered to cause moderate impact to forest resources. Disease centers range in size from 1 tree to 10 acres (4 ha, several hundred trees) and contain groups of dead trees interspersed with and surrounded by symptomatic and healthy live trees. In a study of young (5- to 28-year-old) Douglas-fir plantations in Washington and Oregon, Hansen and Goheen (1988) reported that 31 percent of the trees were killed. In the most heavily affected Douglas-fir plantations in southwestern Oregon and northwestern California, stocking levels were found to be reduced by as much as 50 percent (DeNitto 1982; Goheen et al. 1983, 1984, 1985). In northern Idaho and Montana, it is rare for BSRD to be found acting as a primary pathogen of Douglas-fir or pines, and the disease is not considered a major concern in forest management. Although annual mortality is relatively small, BSRD is a concern to those who harvest pinyon pine for Christmas trees or utilize pine nuts for food in the Intermountain Region. It has been speculated that the occurrence of BSRD, at least *L. wageneri* var. *pseudotsugae*, could increase in areas where climate change physiologically stresses the host trees (Ayres and Lombardero 2000).

Black stain root disease can result in increased plant and animal diversity from tree mortality and gap creation. In pinyon pine stands affected by BSRD in southwestern Colorado, shrub layer composition, diversity, and cover did not differ between disease centers and unaffected surrounding woodlands, but cover and composition of the herbaceous layer were significantly different (Kearns and Jacobi 2005). In the northeastern United States, root disease centers caused by *Leptographium* species are associated with increased species diversity related to openings and hardwood encroachment.

Management

In southwestern Colorado, tree removal, soil fumigation, and placement of a mechanical polyethylene barrier between healthy and diseased trees were evaluated for their ability to limit lateral spread of BSRD centers in pinyon pine. None of the treatments was effective at preventing expansion of mortality centers (Sharon and Johnson 1987). At this time, management of BSRD in pinyon pine is limited to identification of high-hazard sites, cultural techniques to maintain tree vigor and spacing to avoid tree-to-tree transmission, and replacing susceptible pinyon pine with nonsusceptible junipers (Cobb 1988). In Douglas-fir plantations in the Pacific Northwest, current management recommendations include planting nonsusceptible species in existing BSRD centers and avoiding site disturbances and tree injuries to prevent establishment of new infection centers. In high-hazard areas, which are those within 1 mile (1.6 km) of existing BSRD centers, recommendations include the avoidance of tractor logging to minimize soil disturbance, planting of mixed species, and timing of precommercial thinnings between June and early August (Hadfield et al. 1986; Hansen et al. 1988; Harrington and Cobb 1988; Rippy et al. 2005). The recommendations for management in ponderosa pine are similar: identify high-hazard areas; avoid monocultures; plant mixed species with a ponderosa pine component of less than 25 percent; and avoid tree wounding, soil compaction, and other site disturbances (Cobb 1988; Hadfield et al. 1986).

Schweinitzii Root and Butt Rot *Phaeolus schweinitzii* (Fr.) Pat.

Biology and Ecology

Schweinitzii root and butt rot (fig. 28) is caused by the fungus *Phaeolus schweinitzii* (Fr.) Pat., a root pathogen that causes extensive brown-cubical decay of host trees' large support roots and basal stem wood (butts). In addition, root tips are killed, causing them to terminate in gall-like swellings that greatly reduce structural support (fig. 29). Schweinitzii root and butt rot affects a broad list of conifer hosts and causes significant damage in Douglas-fir, Sitka spruce, western larch, western hemlock, and western white pine in western North America (Hagle and Filip 2010). In the Lakes States, eastern larch and white and black spruces are most commonly damaged, whereas in the Southeast, damage occurs primarily in mature and old-growth pine trees, young slash pines growing on old naval stores sites

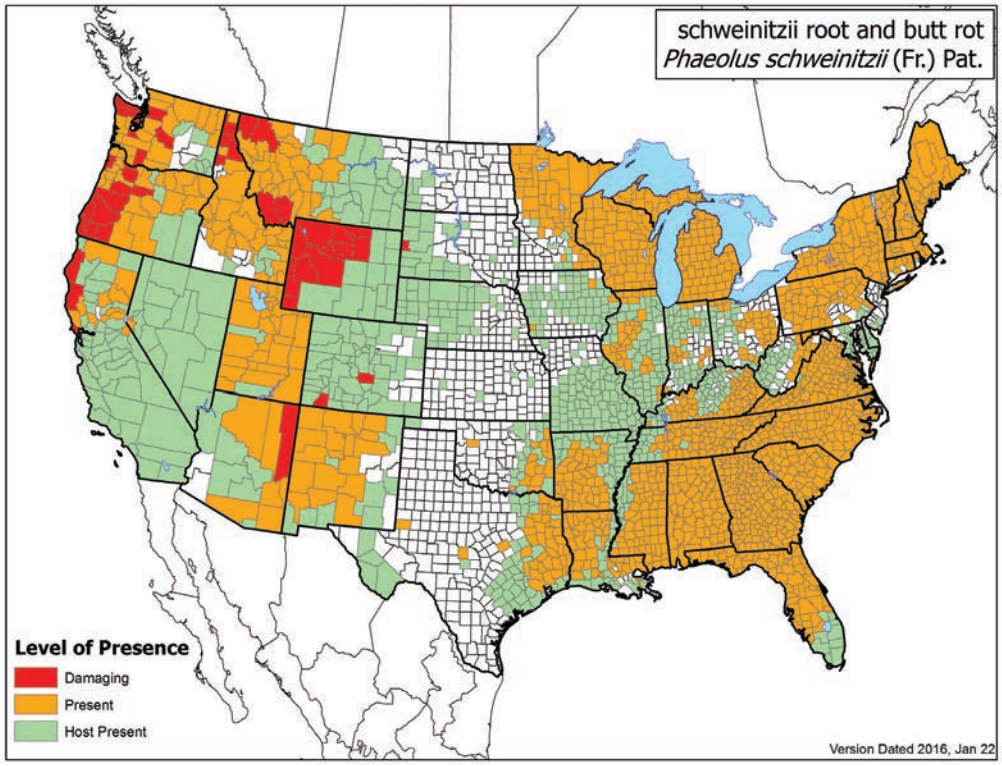

Figure 28—Distribution of hosts and damage caused by schweinitzii root and butt rot (*Phaeolus schweinitzii*) at the county level across the contiguous United States. In green counties, the hosts are present, but the specific root disease has not yet been detected although not all areas have been surveyed. In orange counties, both the tree hosts and the root disease are present. In red counties, the root disease is considered damaging in multiple forest stands to such an extent that management is affected.

Figure 29—Gall-like swelling of Douglas-fir roots caused by schweinitzii root and butt rot (*Phaeolus schweinitzii*) (top) and *P. schweinitzii* fruiting bodies (bottom left and right) (photos: H. Kearns, U.S. Forest Service).

(Blakeslee and Oak 1980), and mature or suppressed eastern white pine stands (Hepting and Downs 1944). *Phaeolus schweinitzii* is not considered an aggressive tree killer; rather, it is relatively slow acting, which results in a very gradual expression of symptoms. Seedlings can be infected and occasionally may be killed; however, it is generally in mature trees that root deterioration causes a measurable decline in tree vigor and increased likelihood of windthrow.

The primary mode of infection is via spores that percolate through the soil, where the fungal pathogen invades fine roots. *Phaeolus schweinitzii* frequently infects young trees and can remain inactive for many years until heartwood is formed within the stem and larger lateral roots. Subsequently, the fungus becomes active in the heartwood, causing brown-cubical decay (Hagle and Filip 2010). Affected trees become stressed due to deterioration of their root systems and often are attacked by other root pathogens, especially *Armillaria* species, and insects like Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins) (Hadfield et al. 1986; Hagle and Filip 2010). Because other co-occurring damaging agents are easier to identify than *P. schweinitzii*, the impact and distribution of schweinitzii root and butt rot are probably underestimated. Although trunk wounds caused by fire or mechanical injury are most likely not infected directly by spores, wounds may exacerbate decay in previously infected roots and butts (Hagle and Filip 2010). Stumps infected with *P. schweinitzii* are not considered important sources of inoculum, and there is little spread of the fungus from tree to tree through root contacts (Hagle and Filip 2010).

Occurrence

Schweinitzii root and butt rot is widely distributed and one of the most common root and butt rots across North America. It is typically found scattered throughout stands rather than in discrete root disease centers. It is very common in old-growth stands in the western United States (Hagle and Filip 2010). An older survey of eastern white pine near Asheville, North Carolina, found 4.5 percent of white pines were affected by *P. schweinitzii* (Hepting and Downs 1944). Currently, an estimated 93,000 acres (37,600 ha) of eastern white pine are considered at high risk for schweinitzii root and butt rot due to age and host frequency (M. Cram, unpublished data).[5]

Impacts

Schweinitzii root and butt rot affects many forest resources including recreation, timber, wildlife habitat, and other forest values and can interact with other agents of forest change. Scattered mortality, especially of dominant trees, and individual windthrown and broken trees are typical. This disease is a major concern in recreation areas with a significant component of older Douglas-fir, western larch, or Sitka spruce because of the high risk of property damage or personal injury from windthrow and breakage. In addition, schweinitzii root and butt rot can extend up into the lower stems of trees, leading to significant volume loss (Hagle and Filip 2010).

Schweinitzii root and butt rot can provide suitable habitat for cavity-nesting animals. In addition, decayed butts and roots infected with *P. schweinitzii* disintegrate, leaving behind brown-rot residues that are very stable and provide important properties, such as increased water-holding capacity, to the organic component of forest floors. These organic components may constitute up to 30 percent of the soil volume in the upper layers (Hagle and Filip 2010). Climate change that increases stress to host trees will likely increase the impacts from agents that decay the roots and butts of trees, including *P. schweinitzii*.

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[5] Data on file with M. Cram, U.S. Forest Service, Forest Health Protection, Athens, GA.

Management

When managing sites with schweinitzii root and butt rot, maintaining good growth and vigor through density management is vital (Hagle and Filip 2010). However, partial harvests that retain predominantly Douglas-fir can result in increased mortality through windthrow, Douglas-fir beetle attack, and breakage of leave trees. It is also imperative to rule out the presence of more aggressive root pathogens on the site, such as *A. ostoyae*, when considering density reduction for managing schweinitzii root and butt rot. Where possible, other species such as ponderosa pine and lodgepole pine, which are considered more resistant, should be retained on the site (Hagle and Filip 2010). There is little risk of infection and mortality of regeneration, especially if the trees will be harvested before age 150 (Hadfield et al. 1986; Hagle and Filip 2010). Most pines are more resistant to the disease than are Douglas-fir or Sitka spruce, so they should be favored in revegetation plantings, especially in a timber or recreation setting.

Tomentosus Root Rot and Red Root and Butt Rot *Onnia* Species

Biology and Ecology

Two species of *Onnia* cause significant root disease in the continental United States: *Onnia tomentosa* (Fr.) P. Karst., which causes tomentosus root rot, and *Onnia circinata* (Fr.) P. Karst., which causes red root and butt rot (figs. 30 and 31). Tomentosus root rot is primarily a disease of Engelmann, white, and blue spruces, but it has been reported in several other hosts including lodgepole pine, western white pine, Douglas-fir, western hemlock, western larch, ponderosa pine, and grand and subalpine firs. *Onnia circinata* is a primary pathogen affecting sand pine over the

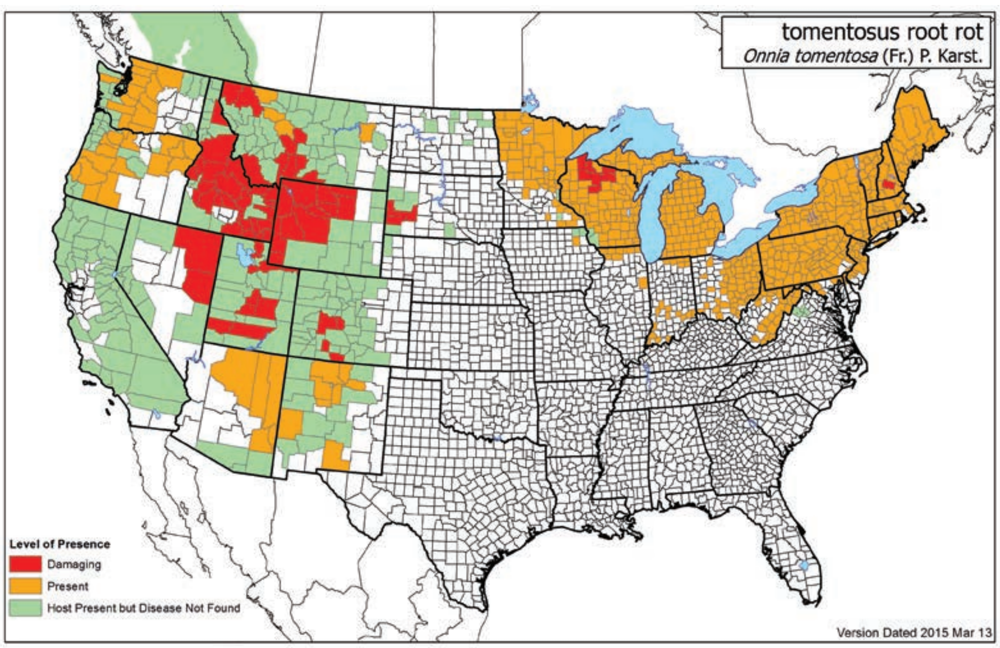


Figure 30—Distribution of hosts and damage caused by tomentosus root rot (*Onnia tomentosa*) at the county level across the contiguous United States. In green counties, the hosts are present, but the specific root disease has not yet been detected although not all areas have been surveyed. In orange counties, both the tree hosts and the root disease are present. In red counties, the root disease is considered damaging in multiple forest stands to such an extent that management is affected.

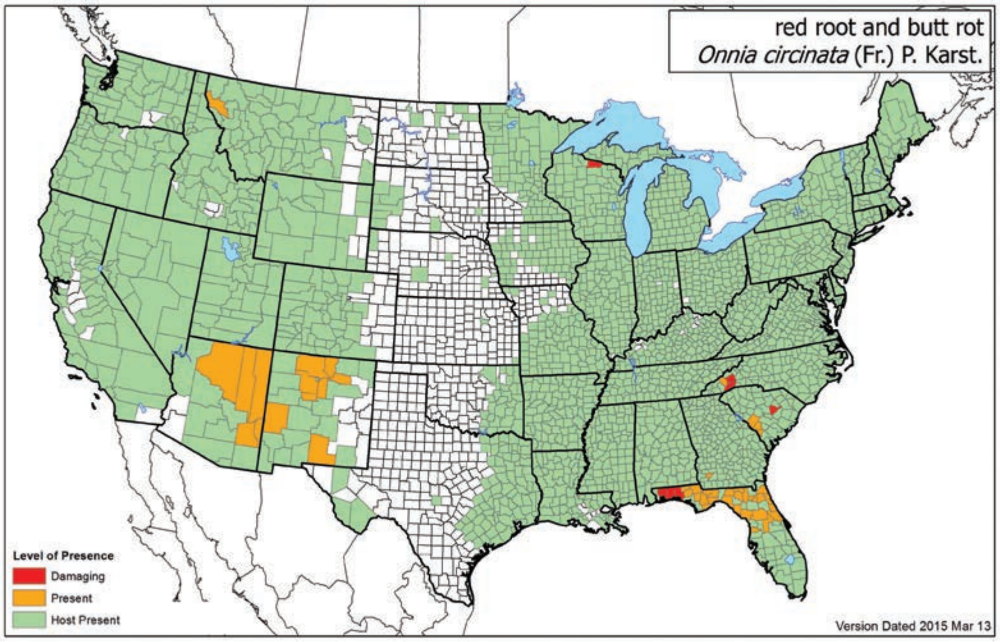


Figure 31—Distribution of hosts and damage caused by red root and butt rot (*Onnia circinata*) at the county level across the contiguous United States. In green counties, the hosts are present, but the specific root disease has not yet been detected although not all areas have been surveyed. In orange counties, both the tree hosts and the root disease are present. In red counties, the root disease is considered damaging in multiple forest stands to such an extent that management is affected.

age of 20 and one of the likely causes of sand pine root disease (Barnard et al. 1985). Other pines affected include slash pine with basal fusiform rust cankers (Boyce 1967) and eastern white pine in plantations older than 30 years (Hepting and Downs 1944). Red root and butt rot also affects mature and old-growth pine trees in the Southeast and is thought to contribute to root and butt rot in lodgepole pine in the Northern Region.

Onnia species most likely enter host trees through direct contact with infected roots or by way of spores that land on wounded roots or root collars (Lewis and Hansen 1991; Sinclair and Lyon 2005). The fungus colonizes the roots and basal stem wood (butts) of the host and over time causes a characteristic white pocket rot of the roots and butts, often culminating in death (fig. 32). Spread occurs primarily by root contacts or fungal mycelia growing short distances through the soil, but spread via spores can also occur. Trees affected by tomentosus root rot are

Figure 32—Decay caused by tomentosus root rot (*Onnia tomentosa*) in Engelmann spruce roots (left), and *O. tomentosa* fruiting body (right) (photos: B. Lockman, U.S. Forest Service).

often reservoirs for endemic populations of spruce beetles (*Dendroctonus rufipennis* Kirby) and spruce engraver beetles (*Ips* spp.) (Lewis and Lingren 2002). When windthrow events trigger an outbreak, these beetles can move from the root disease centers, or groups of root-disease-infected trees, into the surrounding forest, causing extensive mortality.

Occurrence

The *Onnia* species are broadly distributed throughout North America (figs. 30 and 31). Tomentosus root rot occurs primarily in temperate spruce forests. It is not known to be widespread in most forests, but when present it can occur as disease pockets (stand openings) that are very difficult to manage. Soil moisture and nutrition, as well as position on the slope, influence where these stand-opening root disease pockets occur.

Red root and butt rot is most often found on pines. Gilbertson and Ryvarden (1986) describe *O. circinata* as being distributed throughout North America, and illustrate its presence in all the western States but Nevada. During the preparation of this current report, the distribution of *O. circinata* was documented in only a few of the States reported in Gilbertson and Ryvarden (1986). A possible explanation for this discrepancy is that the fruiting structures (sporophores) of *O. circinata* and of *O. tomentosa* are extremely difficult to differentiate in the field, and most documentation of presence and damage have probably been credited to *O. tomentosa*. It is important to resolve this confusion in the future, as proper identification is necessary for management recommendations.

Impacts

Onnia-caused root diseases can have significant impacts on forest resources including recreation, wildlife habitat, timber, and other forest values. The death of trees, windthrow, reduced growth, loss of volume after decay moves up into the stem, and the spread of the disease into nearby trees reduce timber volume and value and site productivity. Where spruce occurs on developed sites, the presence of *O. tomentosa* may result in damage to property or may endanger life due to falling trees (fig. 33), resulting in the permanent closing of developed sites (Lockman and Steed 2014). Stand openings caused by tomentosus root rot influence the structure of the forest canopy, which could have either a positive impact or a negative impact on wildlife habitat, depending on whether wildlife species favor openings or a continuous canopy.

Figure 33—Tree failure of live Engelmann spruce at a developed site in Utah due to extensive decay caused by tomentosus root rot (*Onnia tomentosa*) (photo: J. Guyon, U.S. Forest Service).

A survey of eastern white pine near Asheville, North Carolina, found 5.3 percent of white pine was affected by *O. circinata* (Hepting and Downs 1944). Currently, an estimated 93,000 acres (37,600 ha) of eastern white pine are considered at high risk for red root and butt rot due to age and host frequency (M. Cram, unpublished data).[6]

[6] Data on file with M. Cram, U.S. Forest Service, Forest Health Protection, Athens, GA.

Climate change that increases stress to host trees will probably increase the impacts from tomentosus root rot (Woods et al. 2010) and from other agents that decay the roots and butts of trees, including *O. circinata.*

Management

Tomentosus root rot is considered a disease of the site; once the pathogen is established, it is very difficult to manage susceptible conifer hosts (Rippy et al. 2005). Often the best strategy is to foster nonsusceptible hosts in the stand openings (Hadfield et al. 1986) until infected roots completely decay, a process that can take more than 30 years (Hunt and Unger 1994). In stands with low levels of disease, replanting host trees at least 10 feet (3 m) from infected stumps can reduce the spread of the disease. Accurate and thorough root rot surveys are needed for this tactic (Lewis et al. 2000).

There has been little research in the management of stands infested with *O. circinata*, and no direct controls are currently available. As with many root diseases, the key to management is prevention of disease by management practices such as avoiding planting species offsite, reducing rotation ages, and preventing wounding of trees during stand entry. For example, to minimize *O. circinata* in sand pine, planting in sites with very deep, well-drained, sandy soils is recommended. Stands should not be allowed to become overly dense, and trees should be harvested prior to overmaturity (Hughes and Smith 2010).

Phytophthora Root Diseases
Phytophthora Species

Biology and Ecology

Phytophthora species belong to a group of organisms called oomycetes, commonly referred to as "water molds" because they grow, reproduce, and infect plant roots in water and saturated soils. Excess water allows roots to become flooded for extended periods of time. *Phytophthora* species produce structures called sporangia that release swimming zoospores (fig. 34). These zoospores are attracted by amino acids and other chemicals exuded from nearby elongating or wounded roots, where they encyst, germinate, and infect the root (Roth et al. 1987; Sinclair and Lyon 2005). Near-saturated soil conditions are required for germination and dispersal of zoospores (Pscheidt 2007).

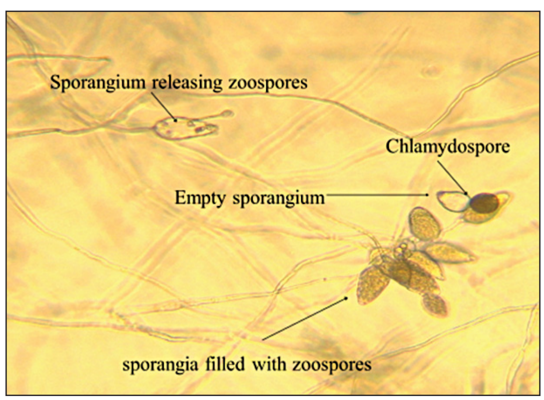


Figure 34—Spores of *Phytophthora lateralis*, the cause of Port-Orford-cedar root disease (photo: provided by U.S. Forest Service).

Although soil saturation is necessary for infection, once *Phytophthora* is inside plant tissues, it continues to colonize the roots regardless of soil conditions. Root infection is progressive and ultimately leads to aboveground symptoms. Initially, only a few fine roots are damaged. As the pathogen invades the root system, plant cells lose the ability to absorb and transport water and nutrients. *Phytophthora* continues to infect more of the root system until it reaches the root crown area, where it kills the cambium and eventually girdles the plant.

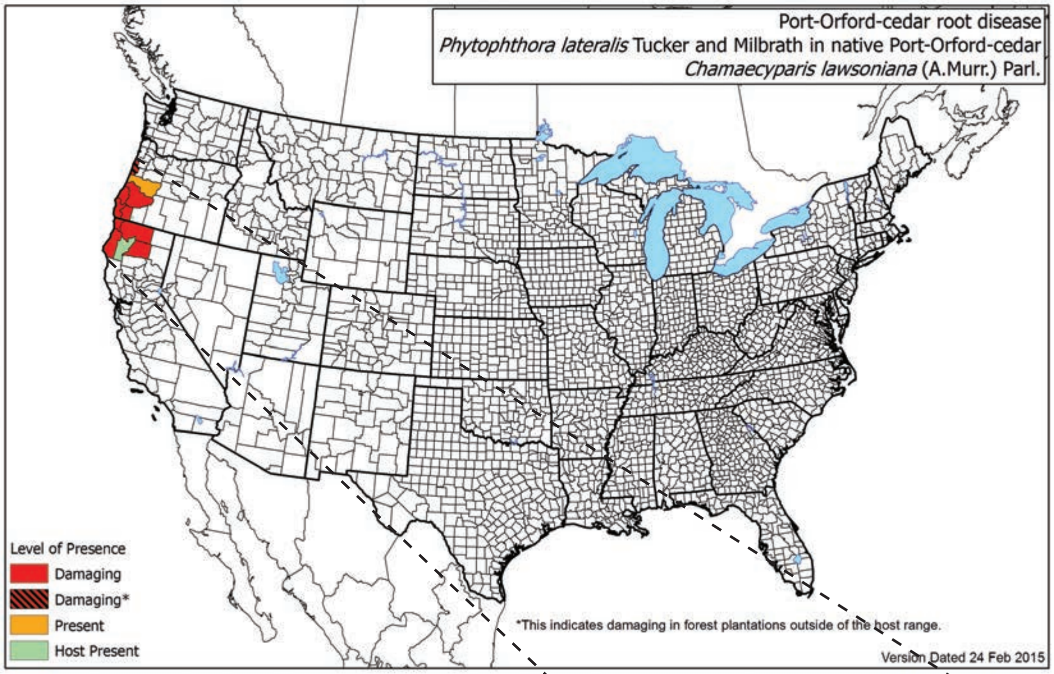
Some *Phytophthora* species produce resting spores (chlamydospores or oospores, or both) in the infected roots that enable the fungus to survive for extended periods of time in the soil. While in or on the soil, the root decomposes, leaving the resting spores behind. Infested soils can then be transferred to new areas via vehicles, animals, hikers, or potted nursery stock (Betlejewski et al. 2011). If susceptible plants are growing or planted in the same area, soil saturation will start the disease cycle again (Parke et al. 2008; Pscheidt 2007; Sinclair and Lyon 2005).

Plant diseases caused by *Phytophthora* species have been some of the most destructive historically and continue to be among the most destructive in the world today. The Irish potato famine of the 1840s was caused by *P. infestans*. The current widespread mortality of trees in Australia has been attributed to *P. cinnamomi*. Sudden oak death and related diseases caused by *P. ramorum* have killed thousands of oaks and other species in the United States (California and Oregon) and Europe. Some forms of a destructive European root disease on alder caused by *P. alni* have been found in Alaska but have not yet been reported in any States within the continental United States. Climate changes resulting in increased winter temperatures, seasonal precipitation shift from summer into winter, and an increased incidence of heavy rains will favor the development and spread of diseases caused by some *Phytophthora* species (Kliejunas et al. 2009; Sturrock et al. 2011). The following is a brief discussion of forest root diseases caused by two *Phytophthora* species in the United States: *P. lateralis* on Port-Orford-cedar in the Pacific Northwest and *P. cinnamomi* on pines in the Southeast.

Port-Orford-Cedar Root Disease *Phytophthora lateralis* Tucker and Milbrath

Occurrence

Port-Orford-cedar has a narrow native range in southwestern Oregon and northwestern California but is a valuable tree species ecologically and economically (Roth et al. 1987; USFS 2006; Zobel et al. 1985). The species has been widely planted as an ornamental (Lawson's cypress) throughout the United States, Canada, and Europe. Port-Orford-cedar root disease (fig. 35) is caused by the exotic root pathogen *Phytophthora lateralis* Tucker and Milbrath. About 9 percent of the mapped Federal lands with Port-Orford-cedar in Oregon and California are infested with *P. lateralis* and contain dead and dying trees (Betlejewski et al. 2003). Pacific yew is the only other native host affected but is much less susceptible than Port-Orford-cedar and becomes infected only if growing close to Port-Orford-cedar (DeNitto and Kliejunas 1991; Murray and Hansen 1997). The pathogen is believed to have been introduced from Asia into the Pacific Northwest in the 1920s on ornamental cedars. It was first identified in native Port-Orford-cedar forests in 1952 (Betlejewski et al. 2011; Roth et al. 1987). The disease is spread by several spore forms that are transported in water or soil, or on other infected plants. High-risk areas for infestation include streams, drainages, low-lying areas, and areas below roads and trails. The spread of the pathogen via root contacts and by water-borne spores results in mortality centers. Because Port-Orford-cedar is commonly a riparian species, dead and dying Port-Orford-cedar are often observed along infested waterways (fig. 36).



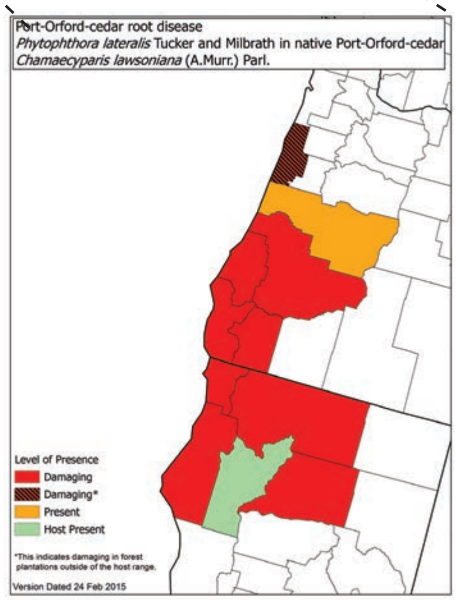


Figure 35—Distribution of hosts and damage caused by Port-Orford-cedar root disease (*Phytophthora lateralis*) at the county level across the contiguous United States. In green counties, the hosts are present, but the specific root disease has not yet been detected although not all areas have been surveyed. In orange counties, both the tree hosts and the root disease are present. In red counties, the root disease is considered damaging in multiple forest stands to such an extent that management is affected.

Figure 36—Dead Port-Orford-cedar killed by Port-Orford-cedar root disease (*Phytophthora lateralis*) along an infested stream in northern California (photo: D. Owen, California Department of Forestry and Fire Protection, used with permission).

Root infection leads rapidly to tree mortality with little or no growth loss before death. Tree mortality can occur within 2 to 3 weeks for seedlings and saplings and may take several years for large trees. In live Port-Orford-cedar with crown symptoms, a distinctive cinnamon-colored stain adjacent to healthy cream-colored inner bark is present at the root collar (fig. 37). Cedar bark beetles (*Phloesinus* spp.) attack some infected trees with reduced vigor.

Figure 37—Characteristic cinnamon-colored staining of inner bark of Port-Orford-cedar infected with Port-Orford-cedar root disease (*Phytophthora lateralis*) in California (photo: P. Angwin, U.S. Forest Service).

Impacts

Mortality of Port-Orford-cedar has economic, social, and ecological impacts. From an economic standpoint, tree mortality can affect the volume of lumber available in both the foreign and domestic markets. Export values of Port-Orford-cedar today are at least three times higher than the domestic market values (Betlejewski et al. 2003). In the past, the Japanese placed a high value on Port-Orford-cedar; stumpage values often exceeded $10,000 per thousand board feet (83.3 ft^3, 2.4 cubic m^3) for higher lumber grades. Domestic products include paneling, decking, fence posts and rails, arrow shafts, and boughs for the floral industry. Besides the economic value of Port-Orford-cedar, Native Americans value the tree for a variety of reasons: family homes and sweat houses, medical purposes, regalia for religious services, and storage containers (Betlejewski et al. 2003). Ecologically, Port-Orford-cedar is found in 43 plant associations in Oregon and California, some of which are unique to certain drainages (Atzet et al. 1996; Jimerson and Daniel 1994). On serpentine soils, Port-Orford-cedar may be the only or most abundant tree species on the site.

Snags of all diameter classes provide abundant habitat for a variety of cavity-nesting birds and wildlife (Betlejewski et al. 2003). As snags decay and fall, Port-Orford-cedar provides habitat as down woody material that remains for decades due to the decay resistance of the wood. Port-Orford-cedar is an important species in riparian ecosystems that provides shade and thus lower stream temperatures. Port-Orford-cedar plant associations contain unique species and regional endemic, rare, or sensitive plants.

Management

Several tools and recommendations have been developed to manage the impacts and spread of *P. lateralis* (Betlejewski et al. 2003; BLM and USFS 2004; Hadfield et al. 1986; USFS 2006; Zobel et al. 1985). Because Port-Orford-cedar is the main host for the disease, favoring other tree species (except Pacific yew) greatly reduces infection and mortality on the site. Disease-resistant Port-Orford-cedar have been developed and are important in revegetating areas that are severely affected by root disease or wildfire (Bower et al. 2000). Resistant Port-Orford-cedar, however, are not immune to infection, and resistant stock should not be planted in areas where eradication of the pathogen is an important management objective or where resistant but infected trees would serve as inoculum sources to adjacent nonresistant Port-Orford-cedar.

Roadside sanitation, or removal of living Port-Orford-cedar, is an effective tool in reducing spread (Goheen et al. 2012; Hadfield et al. 1986) because the pathogen infects only living hosts. Another common technique is separating forest operations in diseased stands from those in disease-free locations, both in space and time. Projects should be scheduled to be completed in the warm and dry months and discontinued when wet conditions favorable to pathogen spread develop. Washing stations to ensure that vehicles and equipment are thoroughly cleaned before moving them to uninfested areas are recommended (Goheen et al. 2012). When water is needed for activities such as forest road construction and maintenance or firefighting, uninfested water sources should be used when possible, or if water is potentially infested, it should be treated with disinfectants such as chlorine bleach.

Littleleaf Disease
Phytophthora cinnamomi Rands

Occurrence

In the southern United States, the pathogen *Phytophthora cinnamomi* Rands is part of a complex of factors that causes littleleaf disease of shortleaf pine and, to a lesser extent, of loblolly pine (fig. 38) (Campbell and Copeland 1954; Mistretta 1984). Other pine species are rarely affected. Littleleaf disease occurs primarily in pine stands established on eroded agricultural sites with clay soils in the southern Piedmont (Oak and Tainter 1988).

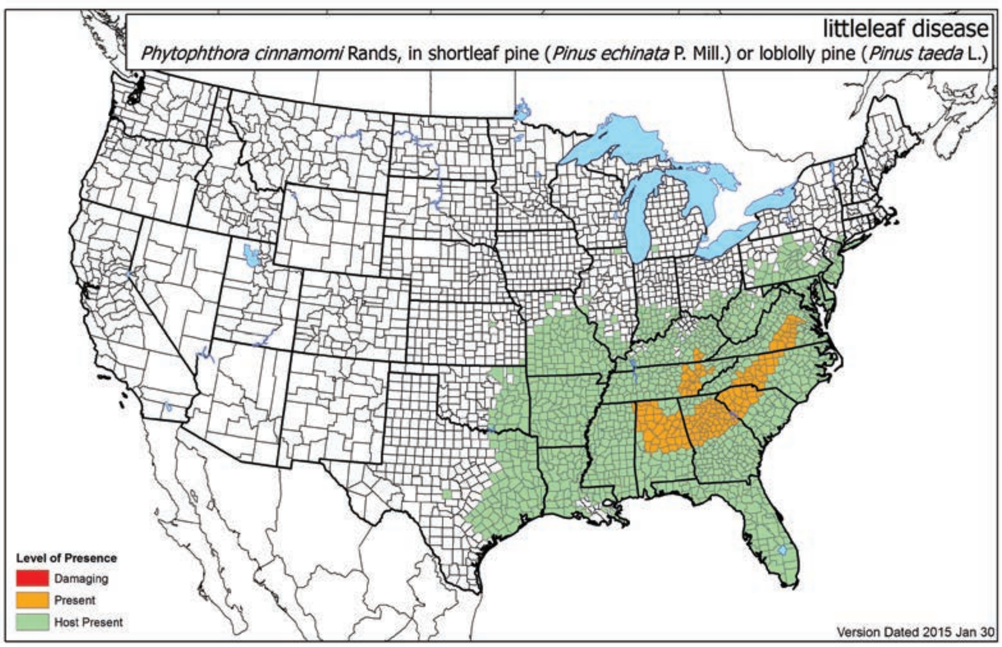


Figure 38—Distribution of hosts and damage caused by littleleaf disease (*Phytophthora cinnamomi*) at the county level across the contiguous United States. In green counties, the hosts are present, but the specific root disease has not yet been detected although not all areas have been surveyed. In orange counties, both the tree hosts and the root disease are present. In red counties, the root disease is considered damaging in multiple forest stands to such an extent that management is affected.

Impacts

A survey in the early 1980s showed littleleaf disease affected 35 percent of the commercial range of shortleaf pine, equaling about 1.4 million acres (567,000 ha), and caused an estimated annual loss of $25 million (Mistretta 1984). Currently, the scale of the disease and losses have been reduced as managers over the past 50 years have converted severely damaged shortleaf pine stands to loblolly pine or other more tolerant species (Sinclair and Lyon 2005). However, loblolly pine stands on sites conducive to littleleaf disease still undergo significant reduced growth and premature losses. The growth decline of affected loblolly pine begins around age 20, with growth culminating at 30 years for trees with severe crown symptoms and 40 years for trees with light crown symptoms (Oak and Tainter 1988). The incidence of loblolly pine with littleleaf symptoms is 15 percent on high-risk, 14 percent on intermediate-risk, and only 1 percent on low-risk sites (Oak and Tainter 1988). Mortality of affected trees occurs on average 6 years after the onset of crown symptoms (Mistretta 1984) (fig. 39).

Figure 39—Symptomatic shortleaf pine infected with littleleaf disease (*Phytophthora cinnamomi*) (photo: S. Fraedrich, U.S. Forest Service).

Management

Foresters use several management methods to prevent or control littleleaf symptoms. Littleleaf disease is prevented largely by converting affected stands to resistant species of hardwoods or pines. Other disease control methods include improving the site by ripping to fragment hardpans prior to planting or fertilizing pine stands on infertile soils (Mistretta 1984).

Sand Pine Root Disease
Phytophthora cinnamomi Rands

Occurrence

Phytophthora cinnamomi Rands is the primary pathogen involved in sand pine root disease (figs. 40 and 41), but other agents involved include *Onnia circinata* and, to a lesser extent, *Phaeolus schweinitzii, Leptographium procerum, Heterobasidion irregulare*, and an *Armillaria* species (Barnard et al. 1985). Sand pine occurs naturally on xeric upland sands in the Florida sandhills (Brendemuehl 1990), where it occupies about 2 million acres (809,000 ha) and is a commercial species planted on infertile, droughty sands. Sand pine root disease is found only in sand pine plantations established with nursery seedlings. Affected stands associated with *P. cinnamomi* are typically located on shallow soils with heavy clay layers or poorly drained soils, which are soils that are not characteristic of natural sand pine sites. The occurrence of *P. cinnamomi* is predominantly in young (less than 15-year-old) sand pine stands, whereas *O. circinata* (cause of red root and butt rot) affects mature to old-growth stands of 20 years and older on a variety of sites (Barnard et al. 1985).

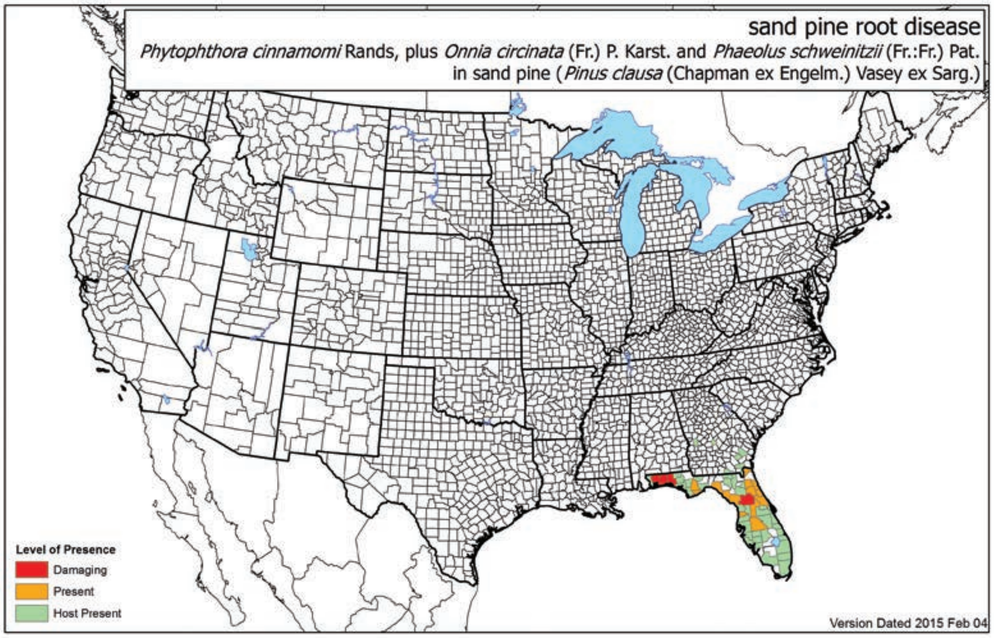


Figure 40—Distribution of hosts and damage caused by sand pine root disease (*Phytophthora cinnamomi* and other pathogens) at the county level across the contiguous United States. In green counties, the hosts are present, but the specific root disease has not yet been detected although not all areas have been surveyed. In orange counties, both the tree hosts and the root disease are present. In red counties, the root disease is considered damaging in multiple forest stands to such an extent that management is affected.

Figure 41—Symptomatic (left) and dead and down (right) sand pines infested with sand pine root disease (*Phytophthora cinnamomi* and other pathogens) (photo: M. Cram, U.S. Forest Service).

Impacts

In Florida, sand pine root disease, the disease complex with which *Phytophthora cinnamomi* is associated, led to losses of $1 million to $2 million per year in the early 1980s (Barnard et al. 1985).

Management

Although it is not clear that *P. cinnamomi* is introduced via seedlings, ensuring seedlings are uninfested or using seed to establish plantations would decrease potential future infestations. Careful evaluation of soils prior to planting to avoid soils with poor drainage or use of methods to fragment hardpans may assist in reducing losses related to *P. cinnamomi*.

White Mottled Rot
Ganoderma applanatum (Pers.) Pat.

Biology and Ecology

White mottled rot (fig. 42) is caused by the fungus *Ganoderma applanatum* (Pers.) Pat. It produces a flat, shelf-like fruiting structure (sporophore) at the base of trees, often near old wounds, and usually close to the soil (fig. 43). The sporophore is commonly called the artist's conk, a name that comes from its use as a drawing medium by artists. The fungus causes extensive decay of the roots and basal stem wood (butts) of trees (fig. 43). Decayed wood is mottled white to light tan, eventually becomes spongy, and may develop black lines. Infections occur from airborne spores or from contacts with infected roots of neighboring trees. Conks can produce billions of airborne spores that infect wounds at the base of trees or on roots. Root-to-root spread leads to groups of infected trees called disease centers. The fungus can persist on sites as a saprophyte for several years after host trees die.

Occurrence

Ganoderma applanatum occurs throughout North America (Sinclair and Lyon 2005). It is found in all 50 States within the United States as a pathogen or as a common wood-decaying fungus of logs and stumps of deciduous and some conifer tree species. *Ganoderma*-caused root disease has been reported in live trees of many species including apple, aspen, basswood, beech, birch, cherry, citrus, cottonwood, elm, hemlock, hornbeam, horse chestnut,

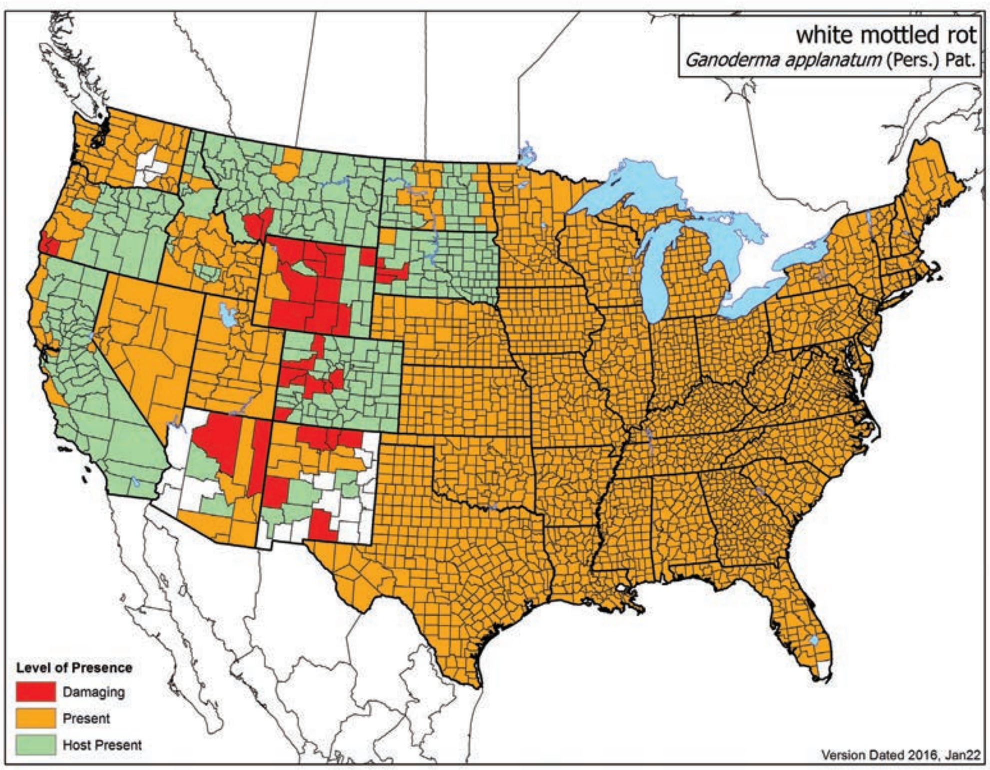


Figure 42—Distribution of hosts and damage caused by white mottled rot (*Ganoderma applanatum*) at the county level across the contiguous United States. In green counties, the hosts are present, but the specific root disease has not yet been detected although not all areas have been surveyed. In orange counties, both the tree hosts and the root disease are present. In red counties, the root disease is considered damaging in multiple forest stands to such an extent that management is affected.

Figure 43—Sporophore of *Ganoderma applanatum* (left), the cause of white mottled rot (right) (photos: M. Fairweather, U.S. Forest Service).

black locust, honeylocust, maple, mulberry, myrtle, oak, spruce, sycamore, tuliptree, sweetgum, and willow. It is a significant problem in cottonwood across North America and in northern hardwoods in the East.

White mottled rot is a common problem of aspen throughout its range and is the most important root disease of aspen in the central Rocky Mountains (Hinds 1985; Ross 1976). Asymptomatic diseased trees, those with healthy-looking crowns, frequently fall while alive. The disease was associated with 86 percent of windthrown, live aspen trees in Colorado (Hinds 1985). Based on two independent systematic surveys of aspen, white mottled rot was causing disease in 47 percent of stands in Wyoming (Blodgett and Lundquist 2008) and in 10, 22, and 28 percent of stands in three national forests in Wyoming and South Dakota (Blodgett et al. 2014). Small trees or trees on poor sites with dry, shallow soils may be killed before decay leads to windthrow.

Impacts

White mottled rot affects many forest products and services including recreation, timber, and aesthetics. Where aspen grows on developed sites, this disease may result in damage to property or endanger life. Live, healthy-looking aspen frequently fall when infected with this disease (fig. 44), so particular attention and consideration are needed for evaluating aspen as potential hazard trees in developed sites. Along with causing indirect tree mortality through uprooting or

Figure 44—Live aspen with roots extensively decayed by *Ganoderma applanatum* (the cause of white mottled rot) at the time of tree failure. Note the sporophore of the fungus at the base of the tree (photo: J. Blodgett, U.S. Forest Service).

snapping at the base, white mottled rot causes direct tree mortality, growth reduction, and wood loss due to decay. It also predisposes trees to other opportunistic lethal agents such as canker pathogens and insects. Because this disease kills and decays roots, it may reduce root-suckering in infested stands, thus reducing regeneration success. White mottled rot combined with other diseases and insects is among the driving forces affecting vegetation succession in the aspen cover type. Climate change that increases stress to host trees will most likely increase the impacts from *G. applanatum* and other agents that decay the roots and butts of trees (Kliejunas et al. 2009; Woods et al. 2010). Impacts from these and other damage agents can result in extensive changes in species composition over time, often with displacement of aspen (Worrall et al. 2013). White mottled rot causes mortality, growth loss, and decay, all of which lead to reduced carbon sequestration.

Management

Clear options for managing white mottled rot are needed. In developed sites, hazard tree inspectors should be trained to recognize the conks. Conks are the only clear indicator of infection and extensive decay in live, standing trees. Fortunately, conks often develop before trees fall or die. Species conversion away from susceptible hardwoods is encouraged in developed sites, especially if this disease is present. Methods for preventing or reducing the incidence of white mottled root rot once trees are infected are not available. However, decay is often associated with wounds, so wounds should be avoided to reduce future infections. Because this disease is a major problem of aspen and a few other deciduous tree species, recognizing the problem and discriminating against susceptible species are also potential management options in nondeveloped forested sites. Species conversion could include complete removal of susceptible host tree species from an infected stand, or selective removal of aspen and other host species during thinning to favor nonhost species.

Conclusions

Root diseases are the most damaging diseases affecting forest trees in the United States (Krist et al. 2014). Once established, root pathogens have long-term impacts on forest ecosystems and resiliency. They can affect site productivity as much as do other factors, such as latitude, elevation, soils, moisture regimes, and exposure. Root diseases can change successional pathways by altering forest composition and structure (Hagle et al. 2000), reduce overall productivity due to mortality and growth loss of host trees (Krist et al. 2014), affect carbon sequestration due to growth loss and mortality of trees and decay of woody material (Jose 2007; Krist et al. 2014), and threaten personal safety due to failures of infected trees (Filip and Goheen 1982a; International Tree Failure Database 2010).

Although root diseases affect forested areas throughout the United States, techniques to locate and measure the incidence and severity of root diseases are very limited or nonexistent in many locations. For example, the distribution maps herein are limited to county-level reports of stand-level damage, rather than precise locations of individual root disease agents. Aerial detection surveys are used to map rapid changes and mortality from forest insects, such as bark beetles and defoliators, but root diseases cause progressive and constant mortality that is difficult to detect and diagnose with these surveys. Newer technologies need to be evaluated to improve our ability to recognize and measure root diseases and their impacts over large landscapes.

More data are needed regarding the impacts of root diseases on growth and mortality of host trees, site factors that affect the presence and severity of root diseases, and interactions between root diseases and other biotic and abiotic agents. Long-term monitoring is necessary to properly measure and evaluate these effects and relationships. Root diseases will have ever-increasing impacts on trees as temperature and precipitation regimes are altered under projected climate scenarios (Kliejunas 2011; Kliejunas et al. 2009; Sturrock et al. 2011). As our nation's forests are subjected to the cumulative stresses of climate change, long-term monitoring will become more crucial for evaluating incidence of and impacts from root diseases.

Many questions about root diseases remain unanswered. Information on the basic biology and taxonomic status is lacking for some pathogens. We do not fully understand the ecological role of many of these root-disease pathogens, or how they function in the ecosystems where they reside. The importance of spores for spread of some pathogens is virtually unknown. Development of management tools, such as effective biological control agents, disease-suppressive soils, and other novel approaches, is needed for these pervasive diseases. Although precise effects of climate change on these pathogens, their hosts, and their interactions are unknown, it is likely that many forest trees will become stressed from climate maladaptation, which will probably increase the deleterious impacts of many root diseases. The influences of forest management practices, such as repeated entries into stands and soil disturbance, on root diseases need to be better understood. Resources are needed to support research for addressing these and other important issues related to root diseases of forests.

Many current management tools focus on changing species composition on sites heavily affected by root diseases. In the western United States, evidence indicates that a major shift in tree species has occurred over the last 80+ years due to fire suppression and the introduction of white pine blister rust, allowing for a significant increase in species susceptible to root disease (Filip et al. 2007; Hagle et al. 2000). In the southeastern United States, longleaf pine was the dominant pine on dry upland soils (Outcalt 2000; Wahlenber 1946), but fire suppression and management have caused a shift away from longleaf pine (Chapman 1932) to loblolly pine. Loblolly pine is more susceptible than longleaf pine to Heterobasidion root disease on high-risk sites (Hodges 1974). Changing species composition to species that are more tolerant to root disease can be done at the time of harvest, but some sites are so heavily infested by root diseases that the current forest cannot be economically managed (Hagle and Shaw 1991; Hagle et al. 1994). Restoration funding will be necessary to make the shift toward root-disease-tolerant species in these areas.

Restoring forest resiliency is a top priority for the U.S. Forest Service and is necessary for forests to survive and remain sustainable and productive in the face of changing climates, major disturbances, introductions of new pests, and evolving societal needs. Adequate knowledge of root diseases and their roles in forested ecosystems is essential to our ability to manage their negative impacts and build resilient forest landscapes.

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Appendix. Common and Scientific Names for Host Tree Species Used in This Paper

Common name	**Scientific name**
Alder	*Alnus* spp.
Apple	*Malus* spp.
Ash, Green	*Fraxinus pennsylvanica* Marsh.
Basswood	*Tilia* spp.
Beech, American	*Fagus grandifolia* Ehrh.
Birch	*Betula* spp.
Birch, Paper	*Betula papyrifera* Marsh.
Cherry	*Prunus* spp.
Citrus	*Citrus* spp.
Douglas-firs	*Pseudotsuga menziesii* (Mirb.) Franco
Douglas-fir, Coastal	*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*
Douglas-fir, Interior (= Rocky Mountain Douglas-fir)	*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.) Franco
Elm	*Ulmus* spp.
Firs, True	*Abies* spp.
Fir, Balsam	*Abies balsamea* (L.) Mill.
Fir, Grand	*Abies grandis* (Dougl. ex D. Don) Lindl.
Fir, Subalpine	*Abies lasiocarpa* (Hook.) Nutt.
Fir, White	*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.
Hemlocks	*Tsuga* spp.
Hemlock, Mountain	*Tsuga mertensiana* (Bong.) Carr.
Hemlock, Western	*Tsuga heterophylla* (Raf.) Sarg.
Honeylocust	*Gleditsia triacanthos* L.
Hornbeam, American	*Carpinus caroliniana* Walt.
Horse chestnut (introduced species)	*Aesculus hippocastanum* L.
Juniper	*Juniperus* spp.
Larch, Eastern	*Larix laricina* (Du Roi) K. Koch
Larch, Western	*Larix occidentalis* Nutt.
Locust, Black	*Robinia pseudoacacia* L.
Maple	*Acer* spp.
Mulberry, Red	*Morus rubra* L.
Myrtle, Oregon (= California Laurel)	*Umbellularia californica* (Hook. & Arn.) Nutt.
Oaks	*Quercus* spp.
Oak, Bur	*Quercus macrocarpa* Michx.
Oak, Pin	*Quercus palustris* Muenchh.

Pines	*Pinus* spp.
Pine, Eastern white	*Pinus strobus* L.
Pine, Jack	*Pinus banksiana* Lamb.
Pine, Jeffrey	*Pinus jeffreyi* Grev. & Balf.
Pine, Limber	*Pinus flexilis* James
Pine, Loblolly	*Pinus taeda* L.
Pine, Lodgepole	*Pinus contorta* Dougl. ex. Loud.
Pine, Longleaf	*Pinus palustris* Mill.
Pine, Pinyon	*Pinus edulis* Engelm.
Pine, Ponderosa	*Pinus ponderosa* Dougl. ex Laws.
Pine, Red	*Pinus resinosa* Ait.
Pine, Sand	*Pinus clausa* (Chapm. ex Engelm.) Vasey ex Sarg.
Pine, Shortleaf	*Pinus echinata* Mill.
Pine, Singleleaf pinyon	*Pinus monophylla* Torr. & Frem.
Pine, Slash	*Pinus elliottii* Engelm.
Pine, Western white	*Pinus monticola* Dougl. ex D. Don
Pine, Whitebark	*Pinus albicaulis* Engelm.
Populus Spp.	*Populus* spp.
Aspen	*Populus tremuloides Michx.*
Cottonwood	*Populus* spp.
Cottonwood, Nar-rowleaf	*Populus angustifolia* James
Cottonwood, Plains	*Populus deltoides* var. *occidentalis* Rydb.
Poplar, Balsam	*Populus balsamifera L.*
Port-Orford-Cedar (=Lawson's Cypress)	*Chamaecyparis lawsoniana* (A. Murr.) Parl.
Spruces	*Picea* spp.
Spruce, Black	*Picea mariana* (Mill.) Britton, Sterns & Poggenb.
Spruce, Blue	*Picea pungens* Engelm.
Spruce, Engelmann	*Picea engelmannii* Parry ex Engelm.
Spruce, Sitka	*Picea sitchensis* (Bong.) Carr.
Sweetgum	*Liquidambar styraciflua* L.
Sycamore	*Platanus occidentalis* L.
Tuliptree	*Liriodendron tulipifera* L.
Willow	*Salix* spp.
Yew, Pacific	*Taxus brevifolia* Nutt.

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