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Armillaria Root Disease in Conifers of Western North America

Introduction

Armillaria root disease, the most common forest root disease in western North America, affects all tree species to some degree and is one of the most complex forest problems to understand and effectively manage. In 1870, Robert Hartig, the father of forest pathology, was one of the first scientists to investigate the disease in Europe. A century later, after a long history of disease observation, research, and treatment, Lewis Roth, a professor of forest pathology at Oregon State University, highlighted the frustration associated with studying the disease by writing, "*Armillaria* has a history of refractiveness to experimentation."

Figure 1. Armillaria root disease can cause understocked openings, as in this Douglas-fir forest in southwest Oregon. USDA Forest Service photo by Joshua J. Bronson.

Armillaria root disease is caused by several species of fungi in the genera *Armillaria* and *Desarmillaria*. Before 1985, all were commonly recognized as one species, *A. mellea*. To date, seven species of *Armillaria* have been reported in western North America (excluding Mexico): *A. solidipes* (formerly known as North American *A. ostoyae*), *A. mellea*, *A. gallica, A. sinapina, A. cepistipes, A. nabsnona,* and *A. altimontana*. Some species of *Armillaria* are often only mildly pathogenic on western conifers or serve as saprophytes in detritus and/or trees killed by other agents. For conifers in western North America, *A. solidipes* is the currently recognized name for the predominant pathogenic species of major concern, and this guide mainly addresses the root disease caused by *A. solidipes*. Although much of the previous work referred to this pathogen as *A. ostoyae*, the pathogen is referred to as *A. solidipes* in this publication.

Figure 2. Armillaria root disease can result in large mortality centers or gaps in older forests, especially in interior western North America. USDA Forest Service photo by Greg Filip.

In coniferous forests of western North America, Armillaria root disease is commonly expressed as scattered mortality of single trees. Armillaria root disease can also cause small, understocked openings in young plantations (fig. 1) and large mortality centers or gaps in older forests, especially in interior western North America (fig. 2). Single clones of *A. solidipes*, such as the "humongous fungus" and the "largest organism in the world," have been estimated to be 2,400 acres (970 ha) in size and at least 2,200 years old in a mixed-conifer forest of northeastern Oregon. Even within the species, *A. solidipes* pathogenicity appears to vary widely, where one clone may cause large mortality centers, another clone may kill only individual trees, and another clone may behave as a saprophyte.

Besides tree mortality, *Armillaria* infections cause root lesions and growth reductions in living, infected trees, which may exacerbate bark beetle attack. Trees of reduced vigor, which could be attributed to inappropriate planting, maladapted trees, poor site quality, excessive drought, overcrowding, or other interacting stresses, are sometimes more susceptible to mortality from Armillaria root disease than more vigorous trees. Susceptibility to infection and mortality from *A. solidipes* varies greatly by interactions among tree species, age, and size, as well as fungal clone and forest stand and site characteristics. Treatments to prevent or alleviate poor host vigor are often recommended to improve tree growth and reduce tree mortality.

Host Species and Susceptibility to Damage

Armillaria has a relatively broad host range that includes hardwood species. All conifer species in western North America are susceptible to damage to some extent (table 1). Interior Douglas-fir, white fir, and grand fir are among the tree species that can be severely damaged by Armillaria root disease in western North America. This disease typically shows only moderate damage to coastal Douglas-fir, other true fir species (*Abies* spp.), hemlocks, western redcedar, spruces, junipers, and most pine species. Larches, most cedar species, whitebark and limber pines, cypresses, yews, sequoias, and redwoods are seldom damaged by Armillaria root disease. In some areas of interior western North America, decades of fire suppression have allowed highly susceptible species, such as Douglas-fir and true firs, to dominate sites that initially comprised fire-adapted and Armillaria root disease-tolerant species, such as pine or larch.

Tree susceptibility to Armillaria root disease can differ markedly by location in ways that are not well understood. For example, ponderosa pine can be severely damaged by Armillaria root disease in areas of south-central Washington near Glenwood, yet the species is only moderately damaged in most other areas. In general, conifer species less than 15 years old are susceptible to damage caused by Armillaria root disease, but resistant species may develop mechanisms that confine root infections as trees age.

Table 1. Relative susceptibility of conifer species to damage by Armillaria root disease in western North America (modified from Goheen and Willhite 2006).

Common Name	Scientific Name	Damage Level
Interior Douglas-fir	*Pseudotsuga menziesii var. glauca*	High
White fir	*Abies concolor*	High
Grand fir	*Abies grandis*	High
Hemlock	*Tsuga species*	Moderate
Western redcedar	*Thuja plicata*	Moderate
Coastal Douglas-fir	*Pseudotsuga menziesii var. menziesii*	Moderate
Bigcone Douglas-fir	*Pseudotsuga macrocarpa*	Moderate
Juniper	*Juniperus spp.*	Moderate
Pine	*Pinus spp.*	Moderate
Spruce	*Picea spp.*	Moderate
True fir	*Abies spp.*	Moderate
Limber pine	*Pinus flexilis*	Low
Whitebark pine	*Pinus albicaulis*	Low
Cedar	*Chamaecyparis spp., Calocedrus decurrens*	Low
Cypress	*Cupressus spp.*	Low
Larch	*Larix spp.*	Low
Coast redwood	*Sequoia sempervirens*	Low
Giant sequoia	*Sequoiadendron giganteum*	Low
Pacific yew	*Taxus brevifolia*	Low

Fungal Biology and Disease Impact

Signs and Symptoms of Infection

Crown symptoms in conifers can vary as a result of severe root infection, but generally the foliage thins and discolors to yellow, then red, and finally brown. Growth of terminal and lateral branches is often reduced. On large, lightly infected or vigorous trees, crown symptoms develop over many years until the tree dies. Some conifer species produce a larger-than-normal crop of cones, known as stress or distress cones, shortly before they die. On small, severely infected or low-vigor trees, crown symptoms may develop rapidly: the foliage quickly discolors, and the tree often dies within a year. On these trees, premature foliage loss and reduced terminal and lateral-shoot growth may not occur. In many cases, trees with Armillaria root disease display no obvious above ground symptoms, but tree growth is reduced.

Trees affected by drought or attacked by mammals, insects, or other fungi, especially other root disease fungi, may produce similar crown symptoms. Because fungi that cause root disease in trees inhabit the root system, positive diagnosis of Armillaria root disease requires further observations, sampling, or both. On conifers, such as Douglas-fir or pines, the infected portions of the lower stem often exude copious amounts of resin that turn white with age (fig. 3). This is especially true for infections by highly pathogenic clones of *Armillaria*. Other infected conifers, such as the true firs, often exude sap at the tree base that turns black with age.

Figure 3. On conifers, such as this Douglas-fir, the infected portions of the lower stem often exude copious amounts of resin that turn white with age. The white fungal mycelium can be seen beneath the bark. USDA Forest Service photo by Kristen Chadwick.

Removing the bark under the resin or exudates reveals the characteristic white, mycelial fans between the wood and bark (fig. 4), which have the texture of dry latex paint. At times, the mycelial fans can also grow into the inner bark (phloem) of infected trees. Mycelial fans derive their common name from the irregular, fanlike striations they typically display. With age, mycelial fans decompose and turn brown or black before disintegrating completely. Their fanlike impressions remain on the inner bark for many years after tree death.

Figure 4. Removing the bark of infected trees reveals the characteristic white mycelial fans between the wood and bark, which have the texture of dried latex paint. USDA Forest Service photo by Craig Schmitt.

Figure 5. Rhizomorphs can be seen growing beneath the bark. Rhizomorphs are specialized *Armillaria* mycelia that grow through the soil and facilitate infections to adjacent roots. Rhizomorphs can be distinguished from roots by their branching patterns and white core. USDA Forest Service photo by Brent Oblinger.

Another common sign of Armillaria root disease is the rootlike cords of mycelia called rhizomorphs. They can be found under the bark of infected trees at the root collar or on the root surface. Rhizomorphs under the bark are flat, black to reddish brown, and up to 0.2 inches (5 mm) wide. They have a compact outer layer of dark mycelium and an inner core of white mycelium. Rhizomorphs can grow up to 3 feet (0.9 m) or more through the soil each year and can facilitate infection of healthy roots from adjacent infected roots or woody debris. In the soil, rhizomorphs appear round rather than flat and are about 0.1 inches (3 mm) in diameter. Rhizomorphs differ in appearance from fine roots because rhizomorphs have a white core instead of the light-brown core within roots. Rhizomorph structure and branching pattern differ by *Armillaria* species.

Figure 6. ***Armillaria solidipes*** **mushrooms generally have a yellow or light brown stalk about 2 inches long with a ring (annulus) just below the gills. USDA Forest Service photo by Blakey Lockman.**

Characteristic mushrooms that are produced in the autumn, especially in wetter environments, can be another sign of Armillaria root disease. In the drier, interior parts of North America, mushrooms occur sporadically. When mushrooms are produced, they are short-lived, often occur in clusters, and are frequently found at the base of infected trees or stumps. Mushroom characteristics vary by species. Mushrooms of *A. solidipes* generally have a stalk that is yellow or light brown and about 2 inches (5 cm) long with a ring (annulus) just below the gills (fig. 6). The cap is light brown to honey-colored and about 2 to 5 inches (5 to 13 cm) in diameter. The upper surface has dark-brown scales, and the underside has light-colored gills that produce light-yellow to white basidiospores. These spores could provide the basis for establishing new *Armillaria* clones, but additional research is needed to better understand their ecological role. Because of the inconsistent occurrence of mushrooms, DNA-sequence analysis is recommended for positive identification of *Armillaria* species.

Armillaria causes a white rot of infected wood, and early decay is water-soaked in appearance. Advanced decay is a characteristic yellow, wet, stringy rot with numerous black zone lines in the wood. After a tree is killed, decay begins in the sapwood and proceeds to the heartwood. Decay at the butt, or base of the tree, generally extends only a few feet (1 m) above ground. Trees frequently die standing rather than by windthrow and, over time, break at one or more points along the trunk, resulting in snags of various heights in the infested area (see fig. 2).

Disease Spread and Host Resistance

Armillaria can survive for decades in buried wood, especially stumps and roots of harvested or killed trees. The fungus spreads from infected wood to adjacent, healthy roots by rhizomorphs in the soil or on the surface of infected roots. The fungus can also spread when healthy roots contact infected roots or wood, causing a lesion at the point of contact.

Trees with good vigor and tree species that are resistant to root disease can confine infections to localized, resinous lesions. Trees that cannot confine the infections eventually die as the fungus moves up the root to the root collar. After mycelia reach the root collar or taproot from an infected root or rhizomorph, the root collar phloem, cambium, and xylem may be destroyed. The infected tree is effectively girdled by a combination of infection and resin flow at the root collar, which results in tree mortality. The rate of tree mortality depends on the tree species, size, and vigor; fungal clone; inoculum potential; and environmental conditions. Small trees may succumb within 1 year, but large trees may take many years to die, especially if they are vigorous and the fungus is confined to portions of the roots or butt of the tree. On vigorous trees, adventitious roots often form to replace roots that are infected and killed.

For interior Douglas-fir, which is severely damaged by Armillaria root disease, the proportion of confined or callused lesions increases with tree age but not as frequently as in larch. Lesions on interior Douglas-fir appear to be mostly progressive (not callused) on selectively harvested sites; however, the spread of *Armillaria* within infected roots is much slower on undisturbed sites.

Coastal Douglas-fir, which is less susceptible than its interior variant to Armillaria root disease when more than 30 years old, produces vigorous callus around lesions more frequently than does interior Douglas-fir. This may explain the relatively high disease tolerance of older, coastal Douglas-fir on many sites.

For western hemlock, which is highly susceptible to Armillaria root disease in some areas, root infection interferes with the initiation of active defense mechanisms such as callus formation around lesions. In highly susceptible species, the advance of the fungal pathogen typically extends rapidly along the root and is rarely confined to the infection lesions.

Species that are more susceptible to infection by *Armillaria* (e.g., grand fir and interior Douglas-fir) produce lower concentrations of phenolics and more sugar in root bark than do root disease-resistant/tolerant species, such as western larch or ponderosa pine.

For western redcedar, which is moderately damaged by Armillaria root disease, lesions are compartmentalized within a barrier zone containing phenolic compounds that restrict the spread of mycelia to adjacent healthy tissue.

In ponderosa pine, which is moderately damaged by Armillaria root disease, the fungus may kill portions of roots distal to infected, resinous lesions. However, mycelia within these girdling lesions rarely advance to the root collar or taproot (progressive lesions) and rarely kill the entire tree on productive pine sites. Instead, mortality of ponderosa pine occurs when the fungal pathogen attacks high on the taproot or root collar.

For young western larch, a species that is seldom damaged by Armillaria root disease, the confinement of root infections within lesions tends to increase in older (85–95 years) trees. Callused lesions may eventually be sloughed with the bark or remain compartmentalized, resulting in stain and decay that are contained within roots or butts. As with ponderosa pine, lethal infections in larch can occur on the taproot or root collar.

Dead root systems may be completely colonized by *Armillaria* by 1 to 5 years after tree death or harvesting, depending on the *Armillaria* clone, tree species, size of the root system, number of infected root lesions, extent of root colonization by insects or other fungi, and associated environmental conditions.

Impacts on the Host Tree and Forest

Armillaria can infect, colonize, and kill apparently healthy trees of all ages, often creating canopy gaps or patches called root disease centers or mortality centers (fig. 7). Extensive root disease centers can result in significantly altered stand structure, density, and fuel profiles.

Figure 7. A mortality center caused by *Armillaria solidipes* in white fir, a highly susceptible species. USDA Forest Service photo by Greg Filip.

Besides tree mortality, *Armillaria* infections may cause crown dieback, resinous-root lesions, internal butt decay, tree-growth reductions, and lower stem deformations. *Armillaria* infections can predispose living trees to subsequent attack by several species of bark beetles. The association between tree wounding and *Armillaria* infection is not well known. Severe wounding of roots or stems could create an entry point for the fungal pathogen, exacerbate existing root infections, trigger bark beetle attack, and possibly result in tree mortality.

Armillaria root disease often is associated with trees stressed by soil disturbance, high stand densities, climate change, maladaptation, abiotic events, other pest attack, or complex interactions between the biotic and abiotic environments. Short-term changes in the climate, such as decreased precipitation or increased temperatures, may stress trees and predispose them to increasing levels of Armillaria root disease and associated bark beetles. Tree stressors likely compromise the host's ability to confine infections within the root tissue, resulting in fungal spread in root systems to the root collar or taproot, and, ultimately, tree mortality.

Armillaria is an ever-present opportunistic pathogen, often receiving an advantage from decreased host vigor. If infected trees are sufficiently stressed, mycelia of even mildly pathogenic *Armillaria* clones can advance in lateral roots toward the root collar and contribute to tree mortality. Such secondary attack usually lacks resinosis or exudates at the root collar, and mycelial fans are not as robust as those of highly pathogenic clones.

The longevity of viable *Armillaria* inoculum in infested soil is directly proportional to the size of infected, woody material. Thus, mycelia within larger, infected stumps and roots remain viable longer and therefore have a higher likelihood of spreading to healthy trees. Large, infected stumps and roots have the twin advantages of space and time to spread disease: larger root systems can infect healthy trees over a greater distance (space) over a longer period (time). Large stumps of many conifers can contain viable *Armillaria* mycelia for over 35 years, and roots of large, infected trees can extend up to 100 feet (30 m) from the stump in open stands.

For interior Douglas-fir, a higher proportion of trees with Armillaria root disease may result in less total basal area, and individual tree-volume reductions can be as high as 27 percent. Also, per acre yield reductions of 7–15 percent of interior Douglas-fir are less affected by the proportion of diseased primary roots per tree than by the cumulative time since infection. In severely infected forests, tree mortality caused by *A. solidipes* has been estimated at 25 ft^3/acre/year (1.7 m^3/hectare/year) on 1,500 acres (607 hectares) in south-central Washington, 50 ft^3/acre/year (3.5 m^3/hectare/year) on 575 acres (233 hectares) in south-central Oregon, and 30 ft^3/acre/year (2 m^3/hectare/year) on 2,500 acres (1,012 hectares) in central Oregon.

In addition to causing mortality and growth loss in infected trees, Armillaria root disease has several other major effects on the forest ecosystem:

1. Individual tree mortality caused by Armillaria root disease can create habitat for cavity-nesting animals in standing and down trees.
2. Stand canopy structure is altered as groups of trees die, break, and windthrow over several decades.
3. Mortality of several trees in groups creates gaps and edges in the forest canopy that form habitat for animal and plant species and often create centers of biodiversity.
4. Long-term gaps resulting from Armillaria root disease may be occupied by dead trees and shrub species with subsequent decreases in shading and increases in land and water temperatures.
5. Tree mortality and subsequent stem breakage or windthrow facilitate nutrient cycling and organic matter development in forest soils.
6. Wildfire frequency can increase if dead boles and branches contribute to fuel loading with subsequent warming and drying within stand openings created by tree mortality.

Root Disease Complexes and Interactions between Bark Beetles and *Armillaria*

The biology of root disease complexes, where root infections involve two or more pathogenic species, is not well understood. Detection and management may be more difficult. When surveying, damage caused by one root pathogen may obscure the presence of another root pathogen, and management of one root disease may not reduce damage caused by another root disease. Laminated root rot, caused by *Coniferiporia sulphurascens* (also known as *Phellinus sulphurascens*), seriously damages Douglas-fir and true firs in western North America. Laminated root rot is often associated with Armillaria root disease and can be masked by mycelial fans without careful examination for *P. sulphurascens* signs in infected roots. Black stain root disease, caused by *Leptographium wageneri*, affects several conifer species in western North America. In Douglas-fir and ponderosa pine, black stain root disease is frequently found with Armillaria root disease and may be associated with thinning stumps and slash. *Heterobasidion* spp., which cause Heterobasidion (annosus) root disease, can infect newly cut stump surfaces and wounds of many conifer species via airborne spores. Heterobasidion root disease may become a problem in thinned or partially harvested true fir stands and low-productivity pine sites. *Heterobasidion* is often present on trees also infected by *Armillaria.* Schweinitzii root and butt rot, caused by *Phaeolus schweinitzii*, and Armillaria root disease are commonly found together damaging Douglas-fir stands in northern Idaho, Montana, and possibly other areas.

Armillaria root disease is important in predisposing trees to bark beetle attack. When bark beetle populations are epidemic, trees of all vigor classes may be attacked. However, when beetle populations are normal, mostly stressed and injured trees are infested, and this stress is often associated with *Armillaria* infection. In some areas, over 95 percent of the trees successfully attacked by bark beetles are infected by root pathogens. Common bark beetle and *Armillaria* associations in western North America include:

1. fir engraver (*Scolytus ventralis*) in grand, white, and Shasta red firs (*Abies magnifica var. shastensis*),
2. hemlock engraver (*S. tsugae*) in hemlocks,
3. western pine beetle (*Dendroctonus brevicomis*), mountain pine beetle (*D. ponderosae*), or pine engravers (*Ips spp*.) in pines,
4. Douglas-fir beetle (*D. pseudotsugae*), Douglas-fir pole beetle (*Pseudohylesinus nebulosus*), or Douglas-fir engraver (*S. unispinosus*) in Douglas-fir,
5. western balsam bark beetle (*Dryocoetes confusus*) in subalpine fir (*A. lasiocarpa*), and
6. silver fir beetle (*P. sericeus*) in Pacific silver fir (*A. amabilis*).

Management To Reduce Infection and Tree Mortality

Disease Survey and Modelling

Before any disease management can be done effectively, it is important to know the exact location and extent of damage caused by Armillaria root disease on a site. A site survey may also detect other important pests that may be the primary or contributing cause of the stand damage. Surveys should be done by systematically mapping the location of the root disease and other pests based on aboveground and belowground signs and symptoms. Tree mortality, crown thinning, bark staining, or resin flow with characteristic mycelial fans beneath the bark, as well as other pest signs and symptoms, should be documented. Because many trees infected by *Armillaria* have reduced growth but show no readily observable symptoms, excavations and observations near the root collar are necessary to conduct a thorough survey. Additionally, maintaining records of the tree species and size classes affected will help develop improved management strategies, especially since Armillaria root disease has a history of differentially affecting some tree species depending on geographic location.

It is a best practice to delineate the boundaries of Armillaria root disease before symptomatic trees are felled. *Armillaria*-caused stain or decay at the cut stump is often absent in infected trees, except for true firs and hemlocks. The infrequent presence of stain or decay on cut stumps, therefore, can prevent accurate estimates of the infection boundaries. Root excavation studies have shown that infected roots often extend 50 to 100 feet (15 to 30 m) beyond the last symptomatic tree; thus, larger trees have potentially greater extension of root infection. In some areas, preliminary assessments of the location and distribution of Armillaria root disease are done with aerial photos. Dead trees and symptomatic live trees can be delineated on photos, which should be followed by ground surveys to verify the causal agents.

Models have been designed to assist in identifying and mapping Armillaria root disease from remote sensing information, and simulation models can help compare vegetation management scenarios on sites where Armillaria root disease occurs. Besides Armillaria root disease, some models, such as the Western Root Disease Model, also can predict impacts of other root diseases, such as laminated root rot and Heterobasidion root disease. Models can be used to compare disease dynamics, behavior, and impact with and without silvicultural treatments, such as tree species manipulation, thinning, partial cutting, clearcutting, and stump excavation. Models have also been designed to predict the future risk of Armillaria root disease and tree mortality caused by other forest pests in the United States.

Tree Species Manipulation

Based on our current understanding of the spread and long-term survival of *Armillaria* in roots, the preferred management alternative in many cases involves taking advantage of the differences in tree species susceptibility to damage by Armillaria root disease (see table 1). By planting moderately or seldom-damaged species or by favoring such species during thinning or partial-tree harvesting, root disease losses can be greatly reduced. These are general guidelines, however, and species susceptibility may differ locally, especially among the species that are moderately damaged by the disease. For example, on some sites coastal Douglas-fir may show little damage while ponderosa pine is severely damaged, whereas the opposite may be true for other sites. The local susceptibility of moderately damaged species can be a useful guide for the proper species to plant or favor on a given site.

If moderately or seldom-damaged tree species are planted or regenerated for 50 or more years, and ingrowth of severely damaged species is periodically removed, losses from Armillaria root disease may be greatly reduced within most of the infested area. If seldom-damaged species are used, some trees may become infected and possibly killed, but at levels much lower than those incurred by severely or moderately damaged species.

If moderately damaged species are interplanted with seldom-damaged species, the moderately damaged species should be adequately spaced to prevent within-species root contact and limit *Armillaria* spread. Even with seldom-damaged species, high levels of *Armillaria* inoculum may eventually cause substantial disease and tree mortality, especially when virulent *Armillaria* clones are present and environmental conditions favor disease development. Maintaining proper spacing is necessary for sustaining the vigor of individual trees, and thus enhancing their ability to confine infections to localized, resinous lesions.

Young Stand (Precommercial) Thinning

Young-stand thinning, or pre-commercial thinning, has been practiced for decades in western North America, especially with Douglas-fir, western hemlock, western larch, and ponderosa pine. With respect to Armillaria root disease, early thinning presents advantages and disadvantages, depending on the situation. Some potential advantages include:

1. Wounded and infected trees can be eliminated.
2. Root-to-root contact and subsequent disease among residual trees may be minimized if thinning is performed early and residual trees are spaced wide enough.
3. Tree growth and vigor may improve.
4. Moderately or seldom-damaged species can be favored.

Some potential disadvantages include:

1. Stumps from harvesting can serve as *Armillaria* inoculum sources.
2. Residual trees may be temporarily stressed from wounding or thinning shock.
3. Damage from other root diseases or pests may be exacerbated.

Figure 8. A precommercially thinned stand of ponderosa pine that was severely affected by Armillaria root disease. After 40 years, thinned pine stands had less *Armillaria*-caused mortality and greater diameter and basal-area growth than unthinned stands. USDA Forest Service photo by Greg Filip.

Armillaria root disease is often associated with infected stumps, and the incidence of subsequent infection and mortality of neighboring trees increases with stump size. Because stumps created by precommercial thinning are relatively small, they generally do not support substantial infection and mortality of residual trees. Precommercial thinning of Douglas-fir can increase *Armillaria*-caused root lesions on residual trees; however, rapid growth of residual trees can enhance callusing of *Armillaria*-caused root lesions, which subsequently become dormant. *Armillaria*-caused mortality of coastal Douglas-fir and other tolerant species may be reduced through precommercial thinning because tree vigor is maintained or improved, the size of the fungal food base is minimized, and most root lesions, should they occur, become callused and dormant.

Individual trees in thinned, *Armillaria*-infected stands often grow faster in diameter than trees in unthinned stands. Initial differences may not be significant but may become significant with time. Resinous lesions on live roots may continue to suppress stem diameter growth despite reduced inter-tree competition in thinned stands. However, early thinning of coastal Douglas-fir in western Oregon and Washington and ponderosa pine in central Oregon has been shown to reduce tree mortality, increase diameter, and increase basal area growth after 30 years (fig. 8). The long-term effects of early thinning on other moderately damaged conifer species have not been demonstrated, so caution is warranted when thinning infected stands. Highly susceptible species, such as interior Douglas-fir, grand fir, and white fir, should be selectively removed when thinning.

Commercial Thinning and Seed-Tree/Shelterwood Harvesting

Commercial thinning and seed-tree/shelterwood harvesting have long histories in western North America. Recently, thinning and removal of understory trees, sometimes followed by prescribed fire, have been used to restore historic forest structure, density, and species composition. These partial cutting practices have advantages and disadvantages regarding Armillaria root disease. Some potential advantages include:

1. Highly susceptible species, such as grand or white fir, can be removed, which reduces inoculum potential and spread of *Armillaria* within the stand.
2. The vulnerability of residual trees is decreased through reduced related stress.
3. Wounded and infected trees can be harvested.
4. Root-to-root contact and subsequent disease spread among residual trees may be minimized if spacing of residual trees is wide enough.
5. Tree growth and vigor may improve.
6. Moderately or seldom-damaged species can be favored or planted.

Some potential disadvantages include:

1. Larger stumps from harvesting may serve as *Armillaria* inoculum sources.
2. Residual trees may be wounded if preventative measures are not followed.
3. Harvesting machinery may compact or displace soils leading to decreases in growth and vigor of residual trees and possibly in subsequent regeneration.
4. *Armillaria*-susceptible regeneration may become established if not periodically removed.
5. Damage from other root diseases or pests may be exacerbated.

Selective harvesting in infected stands, especially severely damaged large trees, has a long history of exacerbating Armillaria root disease, likely due to a buildup of *Armillaria* inoculum in infected stumps of harvested trees. The effects of partial harvesting in *Armillaria*-infected conifer stands vary with geographic areas or plant associations.

Retaining moderately and seldom-damaged species as seed trees or shelterwood and/or planting these species after harvesting may reduce *Armillaria*-caused mortality. In sites with Armillaria root disease severely damaged species, such as interior Douglas-fir, grand fir, and white fir, should be selectively removed when thinning or harvesting for seed-tree or shelterwood systems.

Clearcutting and Regeneration

Clearcutting often presents fewer problems for root disease management than other types of regeneration harvesting, such as seed-tree and shelterwood harvesting, because subsequent removal after clearcutting leaves few residual trees to die, windthrow, or exacerbate damage to subsequent regeneration. *Armillaria* may continue to spread, however, from infected stumps to susceptible regeneration within the clearcut if infected stumps and roots are not removed.

The species and type of regeneration (planted, natural, or advance) will determine the potential disease damage. Planting allows the establishment of seldom-damaged species. Seedlings must be from appropriate seed zones or *Armillaria* may cause severe damage. In addition, seedlings should not be planted next to infected stumps in order to minimize the chance for the pathogen to move from stump roots to infect roots of the planted seedlings. Natural regeneration may exacerbate root disease if highly susceptible species are allowed to regenerate. Advance regeneration may already be infected with *Armillaria* before the overstory is harvested and, therefore, may pose a high risk of future root disease. Practices that retain living trees within clearcuts may influence *Armillaria* populations and proportion of susceptible host trees in the future stand. Leaving severely or moderately damaged species on the site may increase root disease levels if infections progress within the residual trees or if the regeneration becomes infected.

Uneven-Age Management

Armillaria root disease is affected by stand structure and species composition. Silvicultural systems, such as uneven-age management, that produce and maintain multistoried stands and climax tree species (especially white or grand fir) may promote root disease. In addition, the harvesting of large, live-infected trees may aggravate Armillaria root disease on a site. If uneven-age management creates stands by means of repeated harvesting and the establishment of susceptible regeneration, then Armillaria root disease may be perpetuated and exacerbated. Mitigating measures that can reduce root disease in multistoried stands include:

1. favoring and regenerating seldom-damaged tree species,
2. improving and maintaining tree vigor through thinning, and
3. removing freshly cut stumps and large roots to reduce *Armillaria* levels.

For example, in severely infected forests composed mostly of highly susceptible species, mortality caused by root disease can be reduced by group-selection harvesting. In this approach, either small openings (0.5–1.5 acres; 0.2–0.6 hectares) are made in the forest, or existing gaps caused by root disease are used. The openings are planted with moderately or seldom-damaged species. Areas surrounding the openings are selectively harvested to favor the species most resistant to root disease and remove the infected trees, including those that are dead, dying, or live and susceptible to root disease. The goal of this approach is to create an uneven-aged forest of mainly disease-tolerant trees while reducing woody fuels.

Prescribed Burning

Prescribed burning has been used as a silvicultural practice for many years, especially in interior western North America. Controlled fire can reduce woody fuels and remove unwanted, understory tree and vegetation species. Prescribed fire in autumn has been shown to reduce *Armillaria* inoculum in wood buried at 3 inches (7.6 cm) below the soil surface but not at 12 inches (30 cm). As a result, the direct effects of prescribed burning or wildfire may not eradicate all *Armillaria* inoculum, since infected roots can occur several feet (ca. 2 m) below the soil line.

The indirect effects of burning on other soil fungi, such as *Trichoderma* spp., which can be antagonistic to *Armillaria* in forests and orchards throughout western North America, may be more important. Isolates of *Trichoderma* spp. obtained from burned soils are more antagonistic to *A. solidipes* in culture than are *Trichoderma* spp. from unburned soils. In addition, ash leachates from prescribed burns in ponderosa pine stands reduce the growth of *A. solidipes* in culture.

In contrast, fire-induced scorching, wounding, or other stressing of residual trees could lead to increased *Armillaria* infections. These infections could proceed to the root collar and potentially exacerbate bark beetle attack, which could result in tree mortality. More research is needed, however, on the effects of prescribed burning or wildfire on the incidence of Armillaria root disease in residual trees and subsequent regeneration.

Stump Excavation and Removal

Stump excavation (stumping) has been used for decades both experimentally and, in some cases, operationally, to reduce Armillaria root disease in western North America. By removing infected stumps and roots of harvested or dead trees, the incidence of root disease on an infested site may decrease with time, even with highly susceptible tree species. On gently sloping, high-quality sites with light soils, removing stumps with a wide-tracked excavator can be an effective, short-term management strategy for Armillaria root disease. As an alternative, whole trees can be pushed over, which causes the root systems to be pulled from the soil.

Potential advantages of stump excavation include:

1. reducing potential spread of *Armillaria* through the removal of infected stumps and large roots,
2. reducing mortality and increasing growth of leave trees or planted seedlings,
3. facilitating the management of economically valuable tree species that are severely or moderately damaged by *Armillaria*, and
4. possibly reducing the impacts of other root pathogens that may also be present in infected stumps and roots.

Potential disadvantages include:

1. the cost and special equipment required for stump excavation and root removal,

2. disturbance and compaction of heavy or waterlogged soils caused by excavators, which can negatively influence beneficial microbial communities,
3. interference of stumps with other management activities, which may warrant their removal from the site (e.g., piling and burning), and
4. excavation limitations due to topography (e.g. steep or rocky ground).

After stump and root removal, *Armillaria* may eventually die within smaller roots left in the ground. However, the fungal pathogen may continue to spread among regeneration for many years. Additional removal of small roots after excavation of the main stump may increase biological effectiveness. Thirty-five years after removing stumps and roots on a severely infested ponderosa pine site in south-central Washington, tree mortality ranged from 23 to 40 percent depending on the level of root removal. The cost of stump and root removal and projected treatment effectiveness should be considered in relation to the projected product yield and value.

Chemical and Biological Control

Although some fumigants have been experimentally tested to control *Armillaria* in the soil and stumps, the use of fumigants has been severely restricted because of environmental concerns. Besides directly killing *Armillaria* mycelia, fumigation can stimulate the growth of antagonistic fungi, such as *Trichoderma* spp.; however, the long-term effects of stump fumigation on disease spread to subsequent regeneration have not been determined on forested sites. As with any pesticide application on forest lands, appropriate licenses and safety precautions are required before any applications are conducted.

In western North America, studies have been conducted with other antagonistic fungi, such as *Hypholoma fasciculare*, applied directly to *Armillaria*-infected stumps to reduce disease spread and subsequent seedling mortality, but more research is needed before this technique can be developed for operational use.

The application of fertilizers to manage Armillaria root disease has had mixed experimental results in forested areas and is currently not recommended to reduce or prevent root disease. Preliminary studies suggest that naturally occurring *Armillaria* (*A. altimontana*) may act to competitively exclude the pathogenic *A. solidipes* in the soil and rhizosphere of western white pine plantations. More studies are needed to determine the extent of this phenomenon and develop management activities to encourage beneficial *Armillaria* and associated microbes that occur naturally on the site.

Management in Christmas Tree Plantations

Armillaria root disease can cause serious problems in commercial Christmas tree plantations, especially in trees established on land recently cleared of *Armillaria*-infected trees. Many species favored as Christmas trees are either severely damaged by *Armillaria* (e.g., interior Douglas-fir, white fir, and grand fir) or moderately damaged (e.g., coastal

Douglas-fir, most pines, and true firs). Seldom-damaged species are rarely grown as Christmas trees.

Regardless of tree species, several options are available to reduce Armillaria root disease. Plantation establishment should be avoided on forested sites with previous Armillaria root disease, and/or stumps and roots should be removed before planting. Sites likely to result in tree stress, such as those that are excessively wet or droughty, should be avoided. Planting with local seed sources and providing adequate nutrient levels may reduce Armillaria root disease. Trenching around infected trees is also recommended to prevent the spread of *Armillaria* rhizomorphs to healthy trees.

Management in Developed Sites, Roadsides, and Worksites

Root disease is one of the leading causes of tree failure that is associated with subsequent damage to humans and their property in western North America. When Armillaria root disease is diagnosed in developed sites, along roadsides, or near worksites, the potential for tree failures in and around root disease centers varies. Tree failure is dependent on tree species and condition, and the presence or absence of adjacent windthrown trees with root disease.

Since *Armillaria*-infected trees often die standing, live-infected and symptomatic trees may not windthrow, but they still have moderate probability of failure. However, live-infected and symptomatic trees have high failure potential if they occur on sites where *Armillaria*-infected, live trees have previously windthrown. Sites with chronic root disease should be treated using one or more of the above techniques to reduce future tree mortality and failure. In all situations, actions must be taken to remove any *Armillaria*-infected trees that threaten human life or property.

No-Management Option

Even with the most rigorous and expensive treatments, Armillaria root disease cannot be completely eliminated from an infested site. In some situations, however, a "do-nothing option" may be the preferred management strategy. As discussed above, forests severely infected with *Armillaria* could continue to die, regenerate to susceptible species, grow, and die again for thousands of years, especially if interior Douglas-fir, grand fir, or white fir is a part of the plant association (see fig. 7). This situation may be desirable for certain management objectives, such as maintaining long-term wildlife habitat or management of designated natural or wilderness areas. The dilemma may be how to prevent the spread of root disease pathogens and associated bark beetles or wildfire to trees in adjacent developed areas, such as road systems, viewing areas, campgrounds, or buildings where dead, dying, structurally compromised, or burned trees pose public safety hazards.

Regardless of ecosystem type, management objectives, or ameliorative treatments, Armillaria root disease will continue to affect the dynamics of an infected forest for centuries, and provides ample opportunity for more observation, research, and management well into the future.

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