

Armillaria Root Disease-Caused Tree Mortality following Silvicultural Treatments (Shelterwood or Group Selection) in an Oregon Mixed-Conifer Forest: Insights from a 10-Year Case Study

Gregory M. Filip, Helen M. Maffei, Kristen L. Chadwick, and Timothy A. Max

ABSTRACT

In 2005, the 10-year effects of two silvicultural treatments (group-selection and shelterwood) on tree-growth loss and mortality caused by *Armillaria ostoyae* were compared with no treatment in a mixed-conifer forest in south-central Oregon. Ten years after treatment, *Armillaria*-caused mortality varied by species and was greatest in Shasta red fir (38% of trees per acre) and white fir (31%) and much less in Douglas-fir (3%) and ponderosa pine (0%). Ten years after harvesting, leave-tree mortality caused by *Armillaria* root disease was not significantly different in treated than in the unharvested units, nor was there significant diameter-growth response to the harvesting even in large ponderosa pine and Douglas-fir. The silvicultural treatments did have some benefits: (1) leave-tree mortality appeared, at least, not to be exacerbated by harvesting; (2) more disease-resistant pine, cedar, and larch seedlings and saplings survived in the shelterwood-harvest stands and group-selection openings than in comparable areas that were not harvested; and (3) living wood fiber was recovered from the treated stands, as well as dying and dead fuels that could exacerbate wildfire losses. Insights into host-pathogen interactions and recommendations for silvicultural options are presented. This is a case study from a single site and should be interpreted as such.

Keywords: white fir, tree wounding and mortality, *Armillaria ostoyae*, shelterwood and group-selection

In the 1980s, the US Forest Service, Klamath Ranger District, in south-central Oregon faced a management dilemma. What, if anything, could or should be done with several thousand acres of mixed-conifer forest that were progressively dying from *Armillaria* root disease caused by *Armillaria ostoyae*? Root-disease gaps ranged in size from a few trees to as large as 10 ac and were steadily expanding. Some of the most productive growing sites for white fir (*Abies concolor*), grand fir (*Abies grandis*), Shasta red fir (*Abies magnifica* var. *shastensis*), ponderosa pine (*Pinus ponderosa*), and coastal Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) in south-central Oregon were affected. It was thought that a significant portion of the infected forest eventually would revert to brush fields and regenerating true fir that would die before achieving any size or desired stand structure. There was concern that the shift in forest structure and density caused by the root disease would have a deleterious effect on wood-fiber production, wildfire risk, visual quality, and key components of late-successional habitat. Traditionally, the susceptible trees often were harvested and the area regenerated by planting ponderosa pine and other species tolerant to *Armillaria* root disease (Morrison 1981, Hadfield et al. 1986, Williams et al. 1986). In many areas, a clearcut essentially would have resulted because there were few disease-tolerant trees remaining. In fact, some clearcutting had already been done in the area in the last 5 years.

There were, however, potential problems with the traditional regeneration-cut option. First, much of the infected area occurred in visually sensitive zones along major highways, trails, or lake-shores. In fact, the Winema National Forest received a national award in 1990 from the American Society of Landscape Architects for an innovative guide for managing the Highway 140 viewshed of the study area. Regeneration of large areas with treatments that either were clearcuts or closely resembled clearcuts was viewed by some as worse than doing nothing. Second, the diseased area was part of a northern spotted owl (*Strix occidentalis* var. *caurina*) management area. Thus, treatment of any kind was severely restricted, and it was highly unlikely that clearcutting would even be permitted. In summary, there was great interest in exploring the effectiveness of other silvicultural treatments, including commercial thinning, shelterwood harvesting, and uneven-age management (Roth et al. 1977, Emmingham et al. 2005, Filip et al. 2009). Also, planting or favoring *Armillaria*-tolerant species has been used operationally but not tested experimentally in southern Oregon. The most *Armillaria*-susceptible species in the Pacific Northwest include white fir, grand fir, and interior Douglas-fir (*P. menziesii* var. *glauca*), whereas least susceptible species include incense-cedar (*Calocedrus decurrens*) and western larch (*Larix occidentalis*) (Hadfield et al. 1986, Goheen and Willhite 2006). Species susceptibility,

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Table 1. Pretreatment (1990) stand quadratic mean diameter (QMD), trees/ac (TPA), basal area/ac (BA), stand density index (SDI), stem wound incidence, *Armillaria* root disease severity rating, inoculum index, and mortality percentage for eight stands of 8–17 ac each.

Treatment/stand	QMD (in.)	TPA	BA (ft ² /ac)	SDI ^a	Wounds (%) ^b	Disease rating (1–9) ^c	Inoculum index ^d	1975–1990 mortality (%)	
								TPA	BA
Group selection									
Harvested/831	15	169	200	330	4	3.7	7	52	28
Unharvested/830	14	109	125	207	0	6.6	51	45	47
Harvested/833	14	296	297	501	19	2.8	18	23	21
Unharvested/832	13	241	207	356	0	5.2	8	32	29
Shelterwood									
Harvested/837	19	46	94	143	17	7.8	29	83	68
Unharvested/836	14	109	121	201	0	5.9	52	41	37
Harvested/835	23	59	168	247	9	4.3	63	63	40
Unharvested/834	12	241	199	345	11	5.0	16	44	37

^a SDI = (QMD/10)^{1.73} × TPA; white fir: upper-management zone (UMZ) = 420, lower-management zone (LMZ) = 280; Douglas-fir: UMZ = 285, LMZ = 190; ponderosa pine: UMZ = 274, LMZ = 183 (Cochran et al. 1994).

^b Percentage of designated leave trees (all species) with ≥1 stem wounds ≥0.1 ft² before harvesting.

^c Mean root disease severity rating for each stand, where 0 = no root disease within 50 ft of plot, 5 = 30–50% canopy reduction from root disease, and 9 = no susceptible tree species left in plot (all dead) (Hagle 1985).

^d Root disease inoculum index = $\sum(\text{dbh}^3 \times \text{yr}/1000)$, where yr = years dead: 0–5 yr = 1.0, 6–10 yr = 0.9, and >10 yr = 0.5 for all known *Armillaria*-infected trees within each variable-radius plot (adapted from Thies and Westlund 2006). Stand inoculum index is the mean of all plots in that stand.

however, can vary by *Armillaria* clone, site and soil characteristics, disturbance history, and plant association (McDonald et al. 1987, Curran et al. 2007).

Single genets (clones) of *A. ostoyae* (“the humongous fungus”) have been estimated to be 2,400 ac in size and 2,200 years old in northeast Oregon (Schmitt and Tatum 2008), and wildfires may have little effect in reducing populations of subterranean root pathogens such as *A. ostoyae* (Ferguson et al. 2003, Fields 2003). A name change to *Armillaria solidipes* has been recently proposed for *A. ostoyae* (Burdson and Volk 2008). Besides tree mortality, *Armillaria* infections may cause crown dieback, resinous-root lesions, tree-growth reductions, lower-stem deformations, stand-structural changes, and down-wood accumulations (Bloomberg and Morrison 1989, Reaves et al. 1993, Cruickshank et al. 1997, 2009, Mallett and Volney 1999, Cruickshank 2002, Fields 2003, Omdal et al. 2004). The association between tree wounding and *Armillaria* infection is not well known. Severe wounding of roots or stems could exacerbate existing root infections and possibly result in tree mortality. *Armillaria* root disease has been associated with stressed trees resulting from soil disturbance, high stand densities, drought, or other pest attack (Wargo and Shaw 1985, Hadfield et al. 1986, Williams et al. 1986, Shaw and Kile 1991). In severely infected forests in the Pacific Northwest, tree mortality caused by *A. ostoyae* has been estimated at 25 ft³/ac per year on 1,500 ac in south-central Washington (Shaw et al. 1976), 50 ft³/ac per year on 575 ac in south-central Oregon (Filip 1977), and 30 ft³/ac per year on 2,500 ac in central Oregon (Filip and Goheen 1982). Dead root systems may be completely colonized by *Armillaria* 1 to 5 years after tree death or harvesting, depending on *Armillaria* genet, tree species, size of the root system, number of infected-root lesions, and extent of root colonization by insects or other fungi.

Because *Armillaria* can persist for millennia on infected mixed-conifer sites and therefore eradication is futile, we tested the hypothesis that silvicultural treatments can reduce growth loss and mortality caused by *Armillaria* and reestablish *Armillaria*-tolerant tree species. The study was conducted in an uneven-aged mixed-conifer forest (but predominantly true fir). The objectives of our study were to determine whether significant differences occur between treated and untreated areas in the amount of 10-year leave-tree dbh-growth loss and mortality with shelterwood harvesting or group-selection harvesting, and to evaluate the frequency of mortality among six *A.*

ostoyae “tolerant” species that were regenerated in the shelterwood and group-selection stands: ponderosa pine, lodgepole pine (*Pinus contorta*), sugar pine (*Pinus lambertiana*), coastal Douglas-fir, western larch, and incense-cedar.

Methods

Site and Stand Description

The study area is southeast of Rye Spur (6,434 ft), 1 mi north of Lake of the Woods and Highway 140, and 25 mi northwest of Klamath Falls, Oregon (latitude 42°24'N, longitude 122°12'W). The area currently is managed by the Klamath Falls Ranger District, Fremont-Winema National Forests, and was part of the Pearce Timber Sale that was implemented in 1995 as part of this study. Elevation ranges from 4,900 to 5,300 ft, with an east aspect and 15–35% slope. Mean annual precipitation, mostly as snow, is 37 in. (Simpson 2007). Soil parent material is mainly colluvium or residuum weathered from volcanic rock or tephra. Soils are well drained, deep (40–60 in.), and classified as Medial-skeletal, amorphous Typic Haplocryands (James Dorr, soil scientist, Fremont-Winema National Forest, personal communication, 2008). Two plant associations occur in the study area: white fir–grand fir/western starflower (*Trentalis latifolia*) and white fir–grand fir/golden chinquapin (*Castanopsis chrysophylla*) (Simpson 2007). White fir and grand fir readily hybridize in the area, are difficult to differentiate, and therefore are called “white fir” in this report. Site index₅₀ ranges from 65 to 90 ft for white fir and from 59 to 93 ft for Douglas-fir (Cochran 1979). The forest is uneven-aged, with scattered dominant 200–800-year-old Douglas-fir and ponderosa pine, an overstory of 50–150-year-old predominantly white fir, and a sparse understory of mostly white fir seedlings and saplings. Where root disease has not caused openings, stand density often exceeds the upper-management zone as defined by Cochran et al. (1994) (Table 1). The area has had some selective harvesting of large-diameter ponderosa pine and Douglas-fir and two clearcuts, 5 and 88 ac, created in 1988 in the eastern half of the area.

The area is infected with a virulent genet of *A. ostoyae* causing abundant mortality gaps within a matrix of healthy-appearing trees (Figure 1). The pattern and dynamics of mortality are similar to an infected area about 25 mi north (Filip 1977). Damage is particularly acute in areas of pure *Abies*. Ponderosa pine and Douglas-fir show some resistance to mortality in the area. Tree mortality (tree/ac



Figure 1. Mortality center in white fir caused by *A. ostoyae* that is typical throughout the study area, especially in designated-shelterwood units.

≥ 5.0 in. dbh) from 1975 to 1990 was 46%, whereas the loss of basal area per acre (BA) was 37%, most of which was caused by *Armillaria* (Table 2). About 46% of the saplings and 11% of the seedlings were dead, about half from *Armillaria*. Most infected and dead true firs also were attacked by the fir engraver (*Scolytus ventralis*), a common *Armillaria* associate (Hadfield et al. 1986, Filip et al. 2007). An adjacent unharvested and similarly infected 100-ac area also is being evaluated for the short- and long-term predictive capability of the Western Root Disease Model in project-planning situations (Maffei et al. 2008).

The species of *Armillaria* causing mortality in the study area was positively identified as *A. ostoyae*, as determined by in vitro fruiting from isolates collected in 1988 (Reaves and McWilliams 1991) and by sequences of the intergenic spacer (IGS-1) region of nuclear ribosomal DNA from isolates collected in 2006 (John Hanna, US Forest Service, Rocky Mountain Research Station, Moscow, ID, personal communication, 2007). There are at least two different genets of *A. ostoyae* present in the study area. Four other *Armillaria* species (*Armillaria calvescens*, *Armillaria sinapina*, *Armillaria gallica*, and *Armillaria cepistipes*) were isolated from a single point within a larger area of *A. ostoyae* (Aaron Smith, US Forest Service, Central Oregon Insect and Disease Service Center, Bend, OR, personal communication, 2008). Mortality caused by other common true fir root pathogens, such as *Phellinus weirii* or *Heterobasidion annosum*, was not evident in our study area. We did not fully excavate root systems, however, so sublethal root infection by these other pathogens and other *Armillaria* species may be present. We found butt rot caused by *H. annosum* and heartrot caused by *Echinodontium tinctorium* in some white and red firs.

Treatment Description

The silvicultural intent of the experimental treatments was to harvest as many of the dead and dying trees as possible, leave the *Armillaria*-tolerant species, and create sufficient openings for successful natural and artificial regeneration of *Armillaria*-tolerant Douglas-fir, pine, cedar, and larch. Although western larch is not native to southern Oregon, it is relatively resistant to mortality from *Armillaria* in its natural range (Goheen and Willhite 2006). In 1990, two silvicultural treatments (shelterwood and group-selection harvesting) were assigned to the area (Figure 2).

Because specific treatments can only be applied to stands with certain tree density/size class/root-disease severity, treatments were not randomly assigned as usual. Instead, the decision to treat or not was randomly assigned to each half-stand. Half of a designated stand was then treated (harvested) and the other half was untreated (control). Shelterwood or group-selection harvesting was designated on the basis of the following stand conditions: more open stands with scattered mortality due to root disease were shelterwood harvested, and healthy-appearing, multistoried stands with some root-disease gaps were treated with group-selection harvests. Leave trees were selected in both harvested and unharvested stands based on tree species and spacing and the best size, form, and vigor.

Two stands of 12 and 18 ac were designated to be harvested with dominant or codominant Douglas-fir and ponderosa pine to serve as shelterwood. Spacing of leave trees was according to district specifications for regeneration of pine and Douglas-fir (50–125 ft² residual BA). Ponderosa pine, blister rust (*Cronartium ribicola*)-resistant sugar pine, incense-cedar, and Douglas-fir were planted in 1996 after shelterwood harvesting according to district specifications.

Two stands of 29 and 18 ac were designated to receive group-selection harvests. One to three openings per stand of 0.5–1.5 ac each were created by removing all tree species ≥ 0.1 in. dbh except for pine and Douglas-fir. Group-selection cuts were located in openings created by root disease. In untreated stands, similar openings were designated in root-disease gaps but were not cut or planted. Ponderosa pine, lodgepole pine, rust-resistant sugar pine, western larch, incense-cedar, and Douglas-fir were planted in the harvested openings in 1996. All areas surrounding the group-cuts were thinned from below to 100 ft² BA and favoring Douglas-fir or pine.

In 1990, only leave trees in stands to be harvested were painted orange by District marking crews. Designated leave trees in unharvested stands were not painted but were marked with aluminum tags during establishment of permanent plots. All harvesting was ground-based and done according to normal district operations as dictated by slope and tree size. All unmarked trees were felled manually, and merchantable trees were transported to designated landings with rubber-tired skidders. Special precautions were taken to avoid wounding of residual trees including bump trees and designated skid trails that could lead to increased risk of mortality by *Armillaria* or stem decay from *H. annosum* or *E. tinctorium*. Slash was lopped and scattered, and burning was not done to avoid tree scorching and wounding.

Site and Stand Data Collected

In 1990, the following data were recorded for each stand: elevation, aspect, slope (percent), inoculum index (Thies and Westlind 2006), root-disease-severity rating (Hagle 1985), and stand density index (SDI) (Cochran et al. 1994). All stands had permanent plots (1 plot per ac) established in 1990 before harvesting. Plots were systematically located on a grid to adequately cover each stand. Each plot consisted of a variable-radius plot (basal area factor 28, 34, or 40) and a fixed-radius circular plot (0.01 ac) with the same centers (Hadfield et al. 1986, Filip et al. 2007). Only trees ≥ 5.0 in. dbh were tallied in variable plots. Only trees < 5.0 in. dbh but ≥ 6 in. in height were tallied in fixed-radius plots. In each plot, only potential leave trees ≥ 0.1 in. dbh were marked with numbered aluminum tags. Tags for trees ≥ 1.0 in. dbh were nailed at breast height; tags for smaller trees were attached by a wire on the first lateral branch.

Data collected for each living plot tree ≥ 0.1 in. dbh included the following: (1) tree number (if present), (2) species, (3) dbh (nearest

Table 2. Stocking and mortality by tree species for all trees in 1990 (before treatment) and for leave trees in 2005 (after treatment) in eight shelterwood and group-selection stands.

	Basal area (ft ²)/ac				Trees (>5.0 in. dbh)/ac			
	Total	Live	Dead from <i>Armillaria</i>	Dead from other causes	Total	Live	Dead from <i>Armillaria</i>	Dead from other causes
(%).....			(%).....			
1990: all trees								
White fir	189	55	37	8	239	50	37	13
Shasta red fir	19	63	22	15	17	63	20	17
Douglas-fir	50	93	2	5	22	91	0	9
Ponderosa pine	21	57	14	29	6	49	30	21
All species	278	63	28	9	284	54	33	13
(SD)	(81)	(18)	(15)	(11)	(112)	(20)	(16)	(5)
2005: leave trees								
White fir	19	69	26	5	8	65	31	4
Shasta red fir	6	72	28	0	2	62	38	0
Douglas-fir	61	83	1	16	16	97	3	0
Ponderosa pine	11	86	0	14	2	86	0	14
All species	98	80	7	13	28	85	13	2
(SD)	(25)	(8)	(15)	(8)	(7)	(17)	(19)	(7)

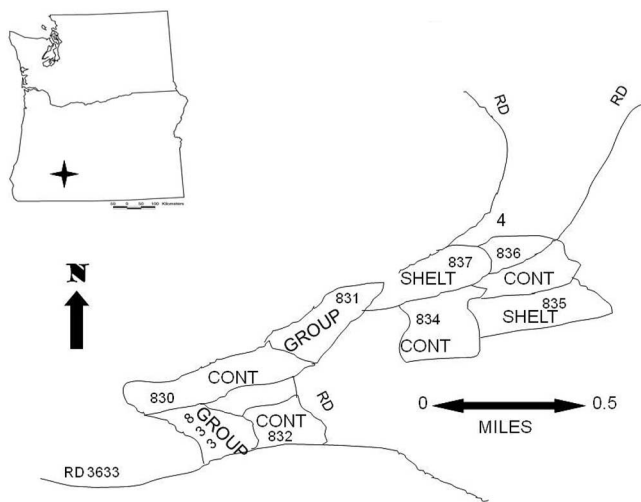


Figure 2. Map showing study area and treatment stand locations. GROUP, group-selection harvest; SHEL, shelterwood harvest; CONT, control (no harvesting). Numbers are treatment stand designations used in Tables 1, 4, and 5.

0.1 in.), (4) number and size (length × width, nearest 0.1 ft) of all stem wounds ≥0.1 ft² in area that penetrated the inner bark, and (5) condition (healthy-appearing or live-infected with *Armillaria*, *H. annosum*, or *E. tinctorium*). Seedlings were tallied only by species and condition.

All dead trees ≥0.1 in. dbh within plots were recorded by species, dbh, years dead, and cause of death. Dead trees that were recorded but not tagged included standing dead trees, as well as any uprooted trees or trees with broken stems as long as they had mostly intact bark (dead 10–15 years). Cause of death was recorded as either *Armillaria* or dead from other or unknown cause. Dead seedlings were tallied by species and cause of death after uprooting each seedling.

In 1990, 91 permanent plots were established in designated shelterwood and group-selection stands (Table 3). Paired stands were similar in most characteristics, especially elevation, aspect, slope, and plant association. Before harvesting, paired stands varied in live trees per acre (TPA), BA, SDI, root-disease-severity rating, inoculum index, and percentage of mortality, but when values were averaged, the four harvested stands were similar to the four unharvested stands (Table 1).

Posttreatment Data Collection and Analysis

Although baseline data were collected in 1990, treatments (harvests) were delayed until 1995. Immediately after harvesting in fall 1995 and 10 years later in 2005, all plots were reexamined, and data were collected as above (Table 3). In 1995 and 2005, live seedlings in plots were counted by species, but dead seedlings were not recorded. Because of the sparse distribution of seedlings and saplings other than white fir, small trees were sampled again in fall 2007 in harvested openings and in designated-harvested openings in the group-selection stands. Within the 0.5–1.5-ac openings, all living non-true firs ≥2 ft height but <5.0 in. dbh were recorded by species in one to three 0.25-ac circular fixed-area plots per opening. The 0.25-ac plots had the same centers as the original 1990 0.01-ac plots.

In 2007, to supplement dbh-growth data collected in 2005, 10–12 Douglas-firs or ponderosa pines were randomly selected and sampled with an increment borer at breast height from three stands: group-selection-harvested, group-selection-unharvested, and shelterwood-unharvested. Cores were collected to determine radial growth 10 years before (1986–1995) and after (1996–2005) stand treatment. Two cores were collected at 90°, and the data were averaged for each tree and stand. All cores were returned to the laboratory, and increments were measured under magnification.

To determine the amount of down-woody material after harvesting, transects were established in 2006 adjacent to each permanent plot within each harvested and unharvested stand. The total amount (tons/ac) of woody material on the ground was estimated according to Brown (1974).

Analysis of variance was used to test for significant ($P \leq 0.05$) differences in 10-year leave-tree dbh increment and mortality by TPA and BA between each treatment pair (harvested versus unharvested). Comparisons between silvicultural treatments (i.e., shelterwood versus group selection) could not be done because of experimental design limitations. The SAS GLM procedure was used for the analysis (SAS 1987).

Results

By 2005, 10 years after treatment, the percentage of leave-tree mortality within all species was less than before treatment (Table 2). In 2005, *Armillaria*-caused mortality was greatest in Shasta red fir (38% TPA) and white fir (31%) and much less in Douglas-fir (3%) and ponderosa pine (0%). The proportion of live white fir in 1990

Table 3. Number of stands, acres, and plots, and years treated and sampled for two silvicultural treatments and unharvested controls in *Armillaria*-infected white fir in south-central Oregon.

Treatment	Number of stands	Total acres	Number of plots	Year treated	Years sampled
Group selection harvested	2	23	25	1995	1990, 1995, 2005, 2006, 2007
Group selection unharvested	2	24	29		1990, 1995, 2005, 2006, 2007
Shelterwood harvested	2	14	18	1995	1990, 1995, 2005, 2006, 2007
Shelterwood unharvested	2	16	19		1990, 1995, 2005, 2006, 2007

Table 4. Ten-year post-treatment (1995–2005) stocking and mortality of saplings (≥ 1.0 to < 5.0 in. dbh) and seedlings (> 6 in. height to < 1.0 in. dbh) within 0.01-ac plots.

Treatment/stand	White fir/ac				Shasta red fir/ac				Douglas-fir/ac			Others/ac ^a		
	Saplings			Seed	Saplings			Seed	Saplings		Seed	Saplings	Seed	
	Live	AO	OT		Live	AO	OT		Live	Dead (AO)		Live	Live	Live
Group selection														
Harvested/831	15	0	0	277	0	0	0	0	0	0	38	0	23	
Unharvested/830	206	0	0	1,869	0	0	0	31	25	0	44	6	6	
Harvested/833	75	0	0	208	100	8	8	58	0	0	42	8	26	
Unharvested/832	75	17	42	600	8	17	8	33	8	0	33	0	0	
Shelterwood														
Harvested/837	188	0	13	450	0	0	0	0	13	0	13	13	52	
Unharvested/836	100	0	22	189	0	0	0	0	22	0	56	0	0	
Harvested/835	120	0	10	450	30	0	0	20	50	0	80	10	20	
Unharvested/834	60	20	10	480	0	0	0	0	10	0	30	0	0	

^a Other species include ponderosa pine, lodgepole pine, sugar pine, incense-cedar, and western larch, most of which were planted. There was no mortality found in saplings of other species. Seedling mortality was not recorded for any species in 2005.

^b Dead AO, dead from *A. ostoyae*; Dead OT, dead from other causes or unknown.

Table 5. Amount of basal area/ac and trees/ac harvested in 1995 in four treated stands.

Treatment/stand	Basal area (ft ²)/ac			Trees (≥ 5.0 in. dbh)/ac			SDI ^a	
	Live 1990	Harvested 1995	Live 1995	Live 1990	Harvested 1995	Live 1995	1995	2005
Group selection								
Stand 831	200	112	88	169	134	35	133	96
Stand 833	297	190	107	296	252	44	160	132
Shelterwood								
Stand 837	94	43	51	46	36	10	69	61
Stand 835	168	34	134	59	23	36	187	181

Percentage of leave trees (all species) with ≥ 1 new stem wounds ≥ 0.1 ft² in size after harvesting in 1995

^a Stand density index (SDI) = $(QMD/10)^{1.73} \times$ live trees/ac (Cochran et al. 1994). White fir: upper-management zone (UMZ) = 420, lower-management zone (LMZ) = 280; Douglas-fir: UMZ = 285, LMZ = 190; ponderosa pine: UMZ = 274, LMZ = 183. SDI is after harvesting for 1995 and 2005.

was substantially reduced by treatment in 1995 (Table 2). Leave-tree mortality from 1990 to 1995 was minor, and all mortality was harvested in 1995. In 2005, there appeared to be more white fir saplings and seedlings in unharvested stands but more red fir saplings and seedlings in harvested stands (Table 4). There were more saplings and seedlings of non-true firs in most of the harvested stands, but only harvested stands were planted with Douglas-fir, pine, larch, or cedar. *Armillaria*-caused mortality of saplings appeared to be greater in the unharvested stands.

Group-Selection Stands

In the group-selection stands, the target of 100 ft² BA for designated leave trees in the matrix surrounding the group cuts was exceeded at 111 and 133 ft² for the two stands after harvesting in 1995. The total residual BA including designated openings in 1995 was 88 and 107 ft²/ac for the two harvested stands (Table 5). The residual stands were 52% white fir, 34% Douglas-fir, and 14% red fir and ponderosa pine. About 56 and 64% BA and 79 and 85% TPA were harvested from the two stands. Although harvested per-

centages were relatively high, only 11% of the leave trees were wounded in stand 831 and none in the other stand.

In the group-selection stands from 1995 to 2005, the two harvested-stand leave-tree mortality losses were 22 and 17 ft² BA (Figure 3A) and 17 and 13 TPA (Figure 3B). In the unharvested stands, leave-tree losses were 12 and 13 ft² BA and 17 and 13 TPA. BA mortality appeared to be slightly greater in harvested stands, but differences were not statistically significant ($P = 0.29$) (Figure 3A). SDI 10 years after treatment was well below the recommended lower-management zone (LMZ) of 183 for ponderosa pine (Cochran et al. 1994) at 96 and 132 for the two harvested stands (Table 5). Guidelines for eastern Oregon (Emmingham et al. 2005) show that the 2005 stocking in harvested stands was below the recommended minimum BA and TPA for white fir and Douglas-fir but within the guidelines for ponderosa pine.

Ten-year leave-tree dbh growth was slightly higher in one of the harvested stands compared to the unharvested stands, but differences were not significant ($P = 0.50$, Figure 4). Increment-core data supported the dbh-growth data where there were no differences in

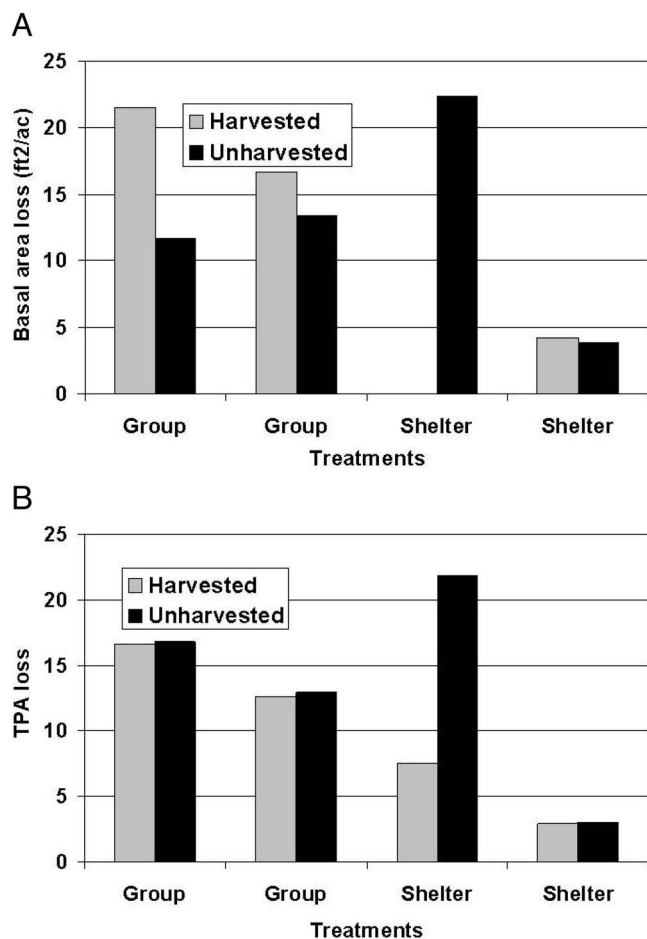


Figure 3. Ten-year (1995–2005) basal area/ac (A) and trees/ac (B) mortality losses mostly from *Armillaria* root disease for designated leave trees by treatment.

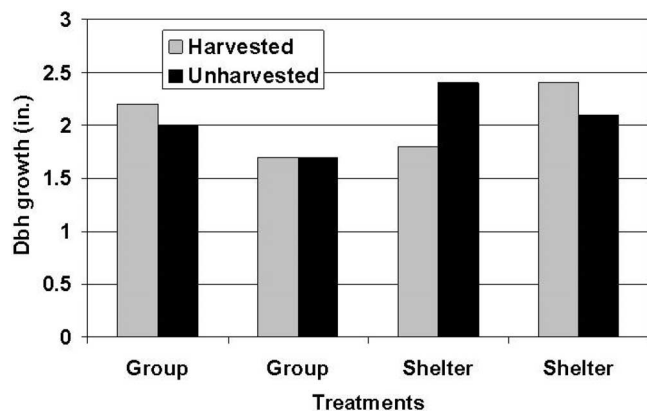


Figure 4. Ten-year (1995–2005) dbh growth for designated leave trees in harvested and unharvested stands.

the ratios of 10-year-radial growth before and after harvesting in the harvested and unharvested stands (0.99 versus 0.99).

In 2005, there were more white fir saplings and seedlings in the unharvested stands than in the harvested stands (Table 4). There were more Douglas-fir saplings in the unharvested stands. Seedlings of other *Armillaria*-tolerant species were more abundant in the harvested stands. In 2007, there were 9 TPA Douglas-fir, 21 ponderosa pine, 3 western larch, 27 lodgepole pine, and 11 sugar pine within harvested openings and 81 TPA Douglas-fir, 6 ponderosa pine, no

larch, 2 lodgepole pine, and 2 sugar pine within designated-unharvested openings. True firs were not sampled in 2007 to concentrate sampling on the *Armillaria*-tolerant species. It appears that the harvested openings increased *Armillaria*-tolerant pine and larch as designed. Douglas-fir, however, was more abundant in the designated-unharvested openings that seeded in as also was observed for Douglas-fir saplings in 2005 (Table 4). We speculate that harvesting machinery may have reduced Douglas-fir advance regeneration in the harvested openings, although the prescription was to retain all Douglas-fir and pine. In 2006 down-woody material averaged 27.3 and 38.4 tons/ac in harvested and unharvested stands, respectively.

Shelterwood Stands

In the shelterwood stands, 46 and 20% BA and 78 and 39% TPA were harvested from the two treated stands (Table 5). Leave-tree wounding was 17 and 5% in the two stands. There were no true fir leave trees in the shelterwood stands, as prescribed, with 90% TPA Douglas-fir and 10% ponderosa pine. Residual BA in 1995 were 134 and 51 ft² for the two harvested stands, slightly higher than the target maximum of 125 ft² for the one stand. From 1995 to 2005, the two harvested-stand leave-tree-mortality losses were 0 and 4 ft² BA (Figure 3A), and 8 and 3 TPA (Figure 3B). In the unharvested stands, designated leave-tree losses were 22 and 4 ft² BA, and 22 and 3 TPA. Mortality appeared to be much greater in one of the unharvested stands, but differences for BA and TPA were not significant ($P = 0.51$ and 0.50). As designed, SDI 10 years after treatment was below the recommended LMZ for ponderosa pine for the two harvested stands (Table 5). Ten-year leave-tree dbh growth showed no significant ($P = 0.80$) differences between harvested and unharvested stands (Figure 4). Increment-core data from the unharvested stand 836 showed that 10-year-radial growth after 1995 was slightly greater than growth before 1995 (ratio=1.1), possibly because of natural thinning resulting from non-leave-tree mortality. In 2005 there were more white fir saplings and seedlings in the harvested stands than in the unharvested stands (Table 4). There were slightly more Douglas-fir seedlings and saplings in the harvested units. Seedlings and saplings of other *Armillaria*-tolerant species, mostly ponderosa pine, occurred only in the harvested stands. Down-woody material averaged 25.5 and 39.8 tons/ac in harvested and unharvested stands, respectively.

Discussion

Understanding how the *Armillaria* infection process differs among conifer species may provide some insight about our observations in treated and untreated stands. For ponderosa pine, *A. ostoyae* may kill portions of roots distal to infected resinous lesions, but these girdling lesions rarely advance to the root collar (progressive lesions) and kill the entire tree on productive pine sites in south-central Washington (Shaw 1980, Reaves et al. 1993) and probably for pines on our site as well. Instead, mortality of ponderosa pine occurs when the fungus attacks high on the taproot or root collar. For young (18–19 years) western larch, root infections are confined to lesions bounded by necrophylactic periderms and phellem, and confined-lesion frequency increases in older (85–95 years) trees (Robinson and Morrison 2001). Callused lesions eventually may be sloughed with the bark or are compartmentalized resulting in stain and decay that are contained within roots or butts (Shigo and Tippet 1981). As with ponderosa pine, lethal attacks in larch occur on the taproot or at the root collar.

For interior Douglas-fir, the proportion of confined or callused

lesions increases with tree age but not as frequently as in larch (Robinson and Morrison 2001). Lesions on interior Douglas-fir appear to be mostly progressive (not callused) on selectively harvested sites in interior British Columbia. However, *Armillaria* spread in infected roots was much slower on undisturbed sites (Morrison et al. 2001). Coastal Douglas-fir, however, produces vigorous callus around lesions more frequently than does interior Douglas-fir (Robinson and Morrison 2001), which probably explains the relatively high disease tolerance of Douglas-fir on our site. Entry et al. (1992) reported that species that are more susceptible to infection by *A. ostoyae* (grand fir and interior Douglas-fir) produce lower concentrations of phenolics and more sugar in root bark than do disease-tolerant species (western larch and ponderosa pine).

Similar studies on *Armillaria* epidemiology, lesion formation, and root chemistry have not been reported for white fir or Shasta red fir, and we did not excavate and examine entire root systems in our study. We speculate, however, that, because of the high relative susceptibility of white and red firs to *Armillaria*, most root lesions probably are progressive with the fungus advancing internally and proximally to the root collar resulting in relatively rapid tree mortality. Vigorous true firs, however, may confine most *Armillaria* infections in roots or root collars, similar to older larch or Douglas-fir. These confined infections on vigorous true firs may be sloughed, or *Armillaria*-caused stain and decay are compartmentalized within roots or butts and manifested externally as butt wounds or malformations with little or no live-crown symptoms. Occluded or compartmentalized root infections, however, probably reduce tree growth by partially or completely reducing root functionality distal to lesions as we speculate occurs on our site. For true firs weakened by drought, climate change, thinning shock, or other stressors, callused lesions may not adequately form with new infections or are breached in old lesions, resulting in *Armillaria* advance to the root-collar and subsequent tree death.

The number and basal area of harvested trees in most treatments in our study area probably were higher than normal because final BA, TPA, and SDI were below the recommended LMZ for most stands after treatment in 1995 and even 10 years later in 2005. Where root disease was severe, some stands already were below LMZ before harvesting in 1990. These stands, however, are not “normal” but have some of the most severe *Armillaria* root disease in western North America. The silvicultural intent of the experimental treatments was to harvest as many of the dead and dying trees as possible, leave the *Armillaria*-tolerant species, and create sufficient openings for successful natural and artificial regeneration of *Armillaria*-tolerant Douglas-fir, pine, cedar, and larch. This was mostly accomplished with minimal damage to the residual trees. The amount of estimated true fir stem decay associated with the old and new wounds was relatively low (0–6.2% ft³ stand volume) in all harvested units. Heartrot associated with these wounds, however, will increase with time.

Ten years after treatment, however, there were no significant differences in leave-tree mortality or diameter growth between harvested and unharvested stands. We speculate that besides callused *Armillaria* lesions on live roots that may have been activated by stand opening, there may be other factors, such as compacted or displaced soils in harvested stands, that reduced any benefit gained by treatment. Unfortunately, we did not monitor soils before or after harvesting. It is also possible that 10 years is not enough time to detect significant treatment differences. For example, significant differences in leave-tree mortality from *Armillaria* root disease were not detected until 30 years and significant diameter-growth differences



Figure 5. A treated stand (A) before thinning (1991), (B) 1 year after thinning (1996), and (C) 10 years after thinning (2005).

until 40 years after precommercially thinning 30-year-old ponderosa pine in central Oregon (Filip et al. 2009). It also appears that after 10 years, leave-tree mortality caused by root disease is, at least, not significantly increased by harvesting; this is an important result considering that *Armillaria* root disease has a long history of being exacerbated by some types of stand harvesting and soil disturbance (Shaw et al. 1976, McDonald et al. 1987, Hagle and Goheen 1988, Morrison et al. 2001, Curran et al. 2007).

Conclusions and Recommendations

This is a case study on a single site, and the results should be interpreted as such. However, we recommend silviculturally treating similar white fir stands with *Armillaria* root disease for several

reasons. Harvesting captured much of the mortality and imminent mortality that would have occurred on such an infected site. At the same time, existing live-forest structure was not radically altered by the two silvicultural treatments (group-selection and shelterwood) as would have been done with traditional clearcut harvesting. Wild-fire risk also was minimized by harvesting that reduced the amount of standing dead and future down-woody material (26.7 versus 37.2 tons/ac), and increased crown spacing among leave trees (Figure 5.) (Fitzgerald 2002). Harvesting followed by planting also shifted the species composition from infection-prone true fir to Armillaria-tolerant Douglas-fir and pine. We also recommend planting or favoring Armillaria-tolerant species. To date, pine, cedar, larch, and Douglas-fir have performed relatively well on our infected sites both within the stands that were shelterwood or group-selection harvested as well as in adjacent clearcut units.

None of the harvest treatments are visible from Highway 140 and assimilate well with the natural pattern of mortality across the landscape. Our root-diseased sites are well documented and will be monitored for several decades. Should wildfire occur, there will be ample opportunity to study the effects of the silvicultural treatments on fire-caused conifer damage and mortality on a severely root-diseased site.

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