FIRE EFFECTS ON FINE ROOTS AND ECTOMYCORRHIZAE OF PONDEROSA PINE AND DOUGLAS-FIR FOLLOWING A PRESCRIBED BURN IN A CENTRAL IDAHO FOREST

A Thesis

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AUTHORIZATION TO SUBMIT
THESIS

This thesis of Gabriel Dumm, submitted for the degree of Master of Science with a major in Forest Resources and titled “Fire Effects on Fine Roots and Ectomycorrhizae of Ponderosa Pine and Douglas-fir following a Prescribed Burn in a Central Idaho Forest” has been reviewed in final form. Permission, as indicated by the signatures below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Fine root and ecto-mycorrhizal (mycorrhizal) densities were evaluated to assess distribution patterns and response to prescribed fire of ponderosa pine (*Pinus ponderosa* Dougl.) and Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) trees in a central Idaho forest. An impact driven soil coring device was used to extract a vertical soil profile, including litter, duff, and "shallow" (upper 10 cm), and "deep" (10 cm and below) mineral soil fractions before and after a mixed severity prescribed fire. Pre-fire fine root weights and mycorrhizal densities were generally highest in shallow mineral soil for both Douglas-fir and ponderosa pine (1.43 to 3.30 g/l and 47.95 to 123.53 root tips/l) and significantly lower in litter and duff horizons than in the other soil horizons. Fine roots and mycorrhizae were completely absent in about 80% of the litter and duff samples, whereas nearly 100% of shallow and deep mineral soil horizons contained these structures. Compared to levels prior to prescribed burning, fine root and mycorrhizal densities were lower by 45 to 78% and 68 to 94%, respectively, in shallow mineral soil (depending on fire severity and host species) at 12 months after an October 2002 prescribed fire. Although no reductions were observed in fine root biomass of shallow mineral soil in the control plots, mycorrhizal density decreased significantly (59-69%) in this horizon. The only significant post-fire change in deep mineral soil was a significant increase (2.21 to 2.96 g/l) in fine root biomass between the pre- and post-fire sample periods in the unburned class of Douglas-fir. Fine root and mycorrhizal densities in litter and duff horizons of burned sample points were not significantly reduced, probably due to low proportion of samples containing any fine roots or mycorrhizae.

For Douglas-fir plots, pre-fire total organic depth (litter depth + duff depth) was significantly correlated with pre-fire fine root biomass in shallow mineral soil. A regression model was fit to predict fine root biomass associated with Douglas-fir using these variables. For ponderosa pine, the reduction in fine root weight (pre-fire weight – post-fire weight) in shallow mineral soil, was significantly correlated with both the reduction (cm) of duff and litter (fine root change), and the residual depth of duff and litter (cm) of burn plot samples. A regression model was successfully fit using these ‘indicator’ variables to predict the reduction in fine root biomass in shallow mineral soil in ponderosa pine plots.

No linear patterns were detected for either fine root weight or mycorrhizal densities based on diameter at breast height or distance from the tree bole. Fine root biomass was significantly different between species in the shallow mineral soil.

Results suggest that even low severity prescribed burning may significantly reduce the biomass of fine roots and density of mycorrhizae in shallow mineral soil for ponderosa pine and fine roots for Douglas-fir in the study area. Additional research is recommended to further evaluate annual patterns in fine root and mycorrhizal densities in the absence of fire, to assess levels and rates of recovery following fire, and to assess long term impacts. The models developed in this case study should also be tested across a variety of sites to determine their generality in similar forest conditions.

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Introduction

Many conifers of the Inland Northwestern United States are well-adapted to periodic disturbance by wildfire. Although the complex biotic and abiotic interactions associated with fire are not yet fully understood, studies of historical conditions have shown that forest structures and composition in many habitats of the Inland Northwest have been altered since the turn of the 20th century, largely as a result of fire suppression, exclusion of cultural fire, timber harvest, and heavy grazing (Steele et al. 1986). Given the region's current forest conditions and managerial goals of restoring historical conditions and regimes and/or improving stand conditions for timber production, an understanding of the roles of fire in ecosystems dependent on this disturbance is critical to developing more sustainable management regimes. Fire effects on below ground resources, in particular, are not well understood. This thesis addresses fire effects on fine roots and ecto-mycorrhizae (henceforth mycorrhizae), potentially valuable components of forest ecosystems and forest health, as well as part of a growing concern for biodiversity and genetic conservation in forest ecosystems.

After more than a century of white/European settlement, Idaho's forests are markedly changed compared to "pre-settlement" conditions. Stand density in terms of both basal area/hectare and numbers of trees per hectare are now higher in many forested areas; stand composition has shifted toward more shade tolerant species; understory species and structural composition have changed; fuel loadings have increased; and a less variable fire regime now favors higher severity fires than in the past (Arno et al. 1997, Brown et al. 1999, O'Laughlin and Cook 2003). For example, before European settlement, ponderosa pine (*Pinus ponderosa* Dougl. [1]) stands in much of central Idaho were open and park-like with few understory trees, a condition likely maintained by low intensity fires at 10-22 year return intervals (Steele et al. 1986). In many places, Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), grand fir (*Abies grandis* (Dougl.) Forbes), or white fir (*Abies*

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[1] All scientific and common names cited according to Hitchcock and Cronquist 1973.

concolor (Gord. & Glend.) Lindl.) now occupy the once open areas between ponderosa pines. Uncharacteristically high fuel loadings are also common in these stands (Arno 1987, Steele et al. 1986). Such changes have obvious ramifications for subsequent fire behavior and, ultimately, ecosystem sustainability.

Fire may directly or indirectly alter decomposition rates, resistance to insects and disease, nutrient uptake, and other factors that influence individual tree health and thus ecosystem health and stability. Land managers and scientists require this information to more fully understand the ways in which forest ecosystems function and the ramifications of management actions, such as prescribed burning. Fire effects on tree health and mortality are generally well-documented. Traditional models of post-fire tree condition have focused on above ground indicators of damage to foliage and/or bark/cambium (Ryan et al. 1988, Peterson 1985, Ryan and Reinhardt 1988, Wyant et al. 1986, Peterson and Arbaugh 1986). However, due to the difficulty in data collection, perceived lack of importance, and perhaps other factors, little is known about the effects of fire on below ground systems.

The study described here focuses on prescribed fire effects on fine roots and accompanying ectomycorrhizal fungi in a ponderosa pine/Douglas-fir stand on the Boise National Forest of central Idaho. Quantities and distributions of these structures may be useful variables in predictive models of post-fire tree mortality, particularly if measurable and reliable above-ground indicators are apparent.

The primary objective of this study was to determine the short-term influences of a prescribed fire on fine root biomass and mycorrhizal densities in different horizons of forest soil associated with ponderosa pine and Douglas-fir trees. A second objective was to describe and quantify fine root biomass and mycorrhizal density associations with environmental factors and assess the reliability of above-ground indicators for estimating changes in fine root biomass and mycorrhizal densities after prescribed fire. A third objective was to describe seasonal variation and measure the rate at which reductions and/or recovery occurred within a year's timeframe.

Research hypotheses were;

H1: Prescribed fire significantly changes mycorrhizal densities and fine root biomass in each soil horizon for Douglas-fir and ponderosa pine.

H2: Mycorrhizal and fine root pre-fire and post-fire density and biomass patterns reflect site conditions associated with each species.

H3: Variation in mycorrhizal densities and fine root biomass occur seasonally, regardless of treatment.

H4: Mycorrhizal densities and fine root biomass vary with distance from tree bole.

H5: Above-ground indicators can be used to predict change in mycorrhizal densities and fine root biomass following prescribed fire.

The following literature review will highlight what is known about the interactions between fire and roots/mycorrhizae. Because of the interrelated nature of these systems, general fire effects on the below-ground environment and tree are also briefly discussed.

Literature Review

Fine Roots

Roots are critical to most land-based plant life as we know it. They anchor the plant to a substrate, absorb water and nutrients from the soil, serve as a major source of organic material to the soil, increase soil porosity and decrease bulk density, store carbohydrates and contribute to a variety of biological activities in and around the rhizosphere where the roots emit secretions and slough dead cells (Waisel et al. 1991). Tree roots are anatomically and systematically similar to the stem having a vascular cambium, secondary growth pattern, and protective bark. Both have the capacity to compartmentalize (isolate) injuries and dead tissue to avoid pathogens. The root system shares close relationships with the shoot and foliage, each supplying material necessary for growth of the others. A reduction in either's capacity will have negative impacts on the other parts of the system (Brouwer and DeWit 1969).

Soil has a great deal of vertical and horizontal heterogeneity, varying in, for example, moisture content, structure, and nutrient content over space and time. Roots tend to be phenotypically plastic and can respond to this relatively heterogeneous environment and thus capitalize on the resources available. However, since soil is normally insulated, it maintains a relatively stable temperature compared to ambient air. Root systems may therefore be particularly sensitive to temperature spikes (Wright 1970). Several studies have noted damage or death to woody roots from temperatures and durations that are commonly tolerated by above-ground portions of the tree (Wong et al. 1971, Ingram and Buchanan 1981).

Roots respire as they assimilate carbohydrates formed through photosynthesis to construct and maintain tissue and to support ion absorption. The respiration rate is a function of the demand for respiratory energy (growth, maintenance, ion absorbtion) and the availability of carbohydrates (photosynthetic ability). Therefore, any factor that affects demand and/or supply of carbohydrates will theoretically alter the respiration rate. As examples, disturbances that limit oxygen availability in the soil (eg. compaction, saturation), disrupt photosynthetic capability (eg. crown scorch/reduction), and/or damage transport mechanisms (eg. fire damage to phloem) can limit respiration in the roots.

Roots with diameters smaller than 0.5 cm have typically been defined as “fine roots”, however researchers have used diameters between <0.01 to 0.1 cm as the threshold cut-off size (Swezy and Agee 1991, Oliveira et al. 2000, Brady and Weil 1999, Vogt and Persson 1991). These narrow structures regulate nutrient uptake, favoring nutrients that are deficient while screening those in excess to prevent toxic levels (Waisel et al. 1991). They are also the site for a potentially advantageous relationship with fungal mycorrhizae.

Mycorrhizae

Mycorrhizae are distinct structures that are produced from root/fungal symbiotic associations with plants. Typically basidiomycetes, mycorrhizal fungi colonize plant roots through direct root-to-root or hyphae-to-root contact, movement of spores with erosive events, transport by animals, or, most commonly, through air dispersal via above ground fruiting bodies (Allen 1991, Brady and Weil 1999). A wide variety of mycorrhizal species have been identified, often associated with specific host species and each with specific environmental parameters in which it can survive (Cairney and Chambers 1999).

Three categories of mycorrhizae have been described; endomycorrhizae (fungus penetrates cell walls, no external mantle forms), ectendomycorrhizae (fungus penetrates cell walls, external mantle forms), and ectomycorrhizae (fungus does not penetrate cell walls, but forms a web in the intercellular spaces in the cortex and on the epidermis of fine roots, covers the root surface with a fungal mantle and alters its appearance). The resulting ectomycorrhizal structure is normally a distinctive whitish, stubby, branched structure that is often visible, or nearly visible, to the naked eye (Allen 1991, Brady and Weil 1999, Dix and Webster 1995).

Mycorrhizae increase a tree's ability to absorb water and soluble nutrients (thereby increasing plant growth), extend root life, and protect the root against harmful pathogens (Harley and Smith 1983, Trofymow and van den Driessche 1991). In exchange, the fungus draws energy (carbohydrates) from the tree, overall contributing to a significant amount of net primary production (Vogt et al. 1982). As the interface between the roots and nutrients, mycorrhizae can buffer changes in soil pH and concentrations of heavy metals, particularly in some species of *Pinaceae* (Read et al. 1985). They can also counteract the effects of phytotoxins whose release may be stimulated by fire (Zak 1971, Roviva and Bowen 1966). Mycorrhizae have also been found to aggregate soil particles with organic secretions, a soil quality necessary for healthy root systems (Borchers and Perry 1990). The vast majority of higher plants all over the world are mycorrhizal, particularly gymnosperms (Harley 1989). It is probable that plant communities evolved with mycorrhizal fungi, which may have even aided plants in the evolution of land-based species (Allen 1991).

Mycorrhizal density at a given site largely depends on nutrient availability and, subsequently, the availability of carbohydrate from the shoot (Pankow et al. 1989, Thompson et al. 1990). Any stress which limits carbon (C) allocation to the roots will affect the mycorrhizae (Andersen and Rygiewicz 1991). Although the mechanisms for these effects are not well understood, when nutrients become scarce (particularly nitrogen (N)), trees allocate a higher proportion of available C to roots (compared to when nutrients are abundant), and mycorrhizal density increases. Conversely, as nutrients become more available, relative C allocation to roots decreases, and thus limits mycorrhizal formation (Read et al. 1985). In the absence of stress or disturbance, a theoretical equilibrium in mycorrhizal density is attained (Andersen and Rygiewicz 1991).

Mycorrhizae are distributed vertically in the soil profile according to species and characteristics of the soil (eg. moisture, nutrient levels, pH) and host (eg. species, health), but occur most often in substrates containing organic materials (Harvey et al. 1976, Harvey et al. 1979, Reddell and Malajczuk 1984, Schoenberger and Perry 1982). This is a curious phenomenom since mycorrhizae are unable to use the organic material directly as a source of C or N, but water holding capacity, bulk density, soil temperature, soil moisture or other physical characteristics of soils containing organic substrates may account for this pattern (Hacskaylo et al. 1973, Harvey et al. 1978). A variety of bacteria also survive on or near the roots (rhizosphere) and emit growth hormones, fix nitrogen, release antibiotics, and increase availability of certain nutrients to the plant, such as iron (Borchers and Perry 1990).

Fire Effects on Trees

Propensity for injury to trees from fire depends on factors such as tree species, climate (including local conditions), topography and the type, amount, and vertical and horizontal continuity of available fuels. Resulting crown scorch/consumption, cambium heating, bark damage, and heat damage to the roots and rhizosphere may (if sufficiently debilitating) cause immediate death or predispose a tree to insects and diseases or loss of competitive advantage from the resulting stress (Ryan 1982). These negative impacts, however, may be offset in fire-adapted species by the advantageous effects of reduced competition and increased nutrient availability, which may account for the contradictory results of post-fire growth studies of ponderosa pine (DeLuca and Zouhar 2000, Arno 1987, Saveland and Bunting 1987, VanSickle and Hickman 1959, Wyant et al. 1983).

For simplicity, damage to trees from fire can be described in three morphological zones: crown, bole, and roots (Ryan 1982). Severe damage in any one of these areas can be lethal. Damage to any one zone is rarely independent of damage to other zones (Agee 1993) and the combined effect of multiple injury in 2 or 3 zones may be synergistic, with greater harm to the tree than would be expected from the individual types and levels of injury (Wyant et al. 1986, Ryan et al. 1988).

Tissue damage from fire is a function of peak temperatures and duration of exposure. Duration is usually disproportionately more important to tissue damage than peak temperature, but tree crowns, because they are typically further away from fuels that support a flaming front of long duration, often escape direct damage from fire. Obviously, fire behavior characteristics not only affect the amount of damage, but also the type of damage. A fast moving, hot burning fire is more likely to damage a tree's crown, whereas a slow, smoldering fire of longer duration increases the risk of damage to the roots and bole cambium (Ryan 1982).

Below Ground Effects of Fire

Fire can affect the physical and chemical attributes of soil, damage underground plant organs, and generally alter the rhizosphere. Direct effects include volatilization of hydrocarbons and nutrients, increased rates of decomposition and nutrient cycling, increased pH, altered C:N ratios, and reduced pore size (increased bulk density), aeration, and water holding capacity (Harvey et al 1989, Neary et al. 1999, DeByle 1981). The magnitude of these impacts are a function of temperature, duration, and conductive characteristics of the soil and litter/humus layers, all of which affect the depth and intensity of heat penetration (Davis 1959, Frandsen and Ryan 1986, Valette et al. 1994, Neary et al. 1999, Raison et al. 1986). Direct changes from fire can decrease water infiltration rates and elevate the potential for soil erosion (Robichaud 2000).

In summary, impacts of fire are influenced by characteristics of the fire itself (a function of fuel, climatic, and topographic influences), the soil (structure, type, moisture, and organic content), and the fuels (structure, type, moisture content, distribution). In fire-adapted ecosystems, changes in the frequency and severity of fire, relative to historic norms, can affect all of these components and therefore may have important consequences for the below ground biotic and abiotic systems.

Fine Roots, Mycorrhizae and Fire

Two general thresholds of soil heating are critical to fine roots and mycorrhizae. At about 60°C, plant organs and mycorrhizae begin to suffer tissue damage and death, but the soil is largely unaltered and rehabitation is readily possible (Agee 1993). At about 200 to 300°C, plant death, physical alteration of the soil qualities and nutrient volatilization begins to occur, ultimately reducing the potential for subsequent recolonization of the site, particularly for mycorrhizae or mycorrhizae dependent species (Reeves et al. 1979, Neary et al. 1999).

Studies of mycorrhizal response to fire have been inconsistent, showing increased, decreased, or unchanged quantities in the post-fire sampling period (Herr et al. 1994, Pilz and Perry 1984, Parke et al. 1984, Harvey et al. 1980, Wright and Tarrant 1958, Schoeberger and Perry 1982, Buchholz and Gallagher 1982). The variation in results may reflect differences in characteristics of the host and/or fungal species, variation in nutrient availability following fire, depth of plant organs, and other, but unidentified factors (Flint 1925, Cairney and Chambers 1999, DeLuca and Zouhar 2000, Driscoll et al. 1999, Flinn and Wein 1977). Since roots and mycorrhizae tend to grow where temperatures are moderate and relatively stable, they are likely ill-adapted to the high soil temperatures that occur during fires that burn with high surface fuel loadings and/or in the high soil temperatures of the post-fire environment.

The magnitude of the mycorrhizal or fine root response is a function of the severity of the fire, the stress avoidance and compensatory characteristics of the mycorrhizae and/or host, and other external factors such as site suitability and the presence and abundance of insects and disease. Ultimately, a new equilibrium is established as the host reacts to primary damage and adjusts to changes in the post-fire environment by altering resources to the roots (Andersen and Rygiewicz 1991).

The vertical distribution of roots and mycorrhizae may influence their post-fire survival potential. Although damage from heat penetration is usually limited to the top few centimeters of mineral soil, heavy fuel loads, such as large slash piles, may result in deeper penetration of high temperatures during fire events (Neary et al. 1999, Valette et al. 1994). If the highest concentration of roots and mycorrhizae coincide with areas of high temperatures, damage may be severe, potentially causing the host to die. Douglas-fir, for example, has a tendency to develop shallow lateral roots that are damaged relatively easily when duff burns down to mineral soil (Ryan 1982). In contrast, fire-adapted species, such as ponderosa pine and western larch, with their relatively deep root systems, are less susceptible to root damage from fire (Flint 1925). However, following uncharacteristically long intervals between fires, even fire adapted species, may develop fine roots in the upper soil, duff, and litter layers where they can be damaged more readily by fire, or fire severity may increase sufficiently for penetration of high temperatures to deeper soil layers (Swezy and Agee 1990). Swezy and Agee (1990) documented a 50-75% decrease in fine root dry weight in the litter/duff and top 10 cm of mineral soil following fire in a central Oregon ponderosa pine forest with high litter and duff loading due to previous fire exclusion. If a critical mass of fine roots is necessary for plant survival, and if they cannot regenerate quickly in the post-fire environment, the high fuel loadings that tend to elevate wildfire severity may significantly damage or even kill otherwise fire resistant trees (Harvey et al. 1976, Harvey et al. 1978).

The post fire environment may also affect fine root and mycorrhizal survival and growth. For example, charcoal has been found to stimulate mycorrhizal growth, a possible adaptation of some species to fire disturbance (Harvey et al. 1976). However, increased surface and soil temperatures following defoliation of crown cover and/or removal of organic surface cover by fire may exceed the optimal temperature range for mycorrhizae (about 8-27ºC, Raison 1979, Parke et al. 1983, Harley and Smith 1983, Raison et al. 1986). Parke et al. (1983) reported that mycorrhizal formation was greatly hindered by extended exposure to soil temperatures of only 29.5ºC in mixed conifer stands of southwest Oregon. Wong et al.

(1971) observed that exposure to soil temperatures of 45ºC for four hours was sufficient to kill the roots of five woody plants thought to represent the spectrum of tolerances to heat (*Fouquieria splendens* Engelm, *Parkinsonia aculeta* L., *Prunus persica* L., *Robinia pseudoacacia* L., and two *Rosa* species). Ingram and Buchanan (1981) reported significant damage to woody roots (*Illicium anisatum*, *Juniperus chinensis* cv. Parsonii, and *Ilex cornuta* cv. Burfordii) exposed to temperatures of 50ºC for only 20 minutes. Microclimatic changes can also alter root respiration rates, further influencing mycorrhizal habitat. For example, soil moisture, which is important to mycorrhizal development, can increase with the lower plant competition or decrease with the higher soil temperatures and/or runoff that may result in the post-fire environment (Harvey et al. 1978, Neary et al. 1999, Raison et al. 1986). Soil bulk density, which also has been found to increase following fire, can also reduce mycorrhizal density and root growth (DeByle 1981, Brady and Weil 1999, Voorhees et al. 1971, Voorhees et al. 1975, Harvey et al. 1976).

Fire can also indirectly affect fine roots and mycorrhizae by altering nutrient availability through changes in soil pH and nutrient composition, cycling, quantity, and distribution in forest soils, the principle store of nitrogen. Nitrogen is particularly important because it is often a limiting nutrient to growth and an important variable in mycorrhizal and fine root densities (Gessel et al. 1973, Andersen and Rygiewicz 1991). Nitrogen (N) is also among those nutrients most easily affected by fire and is often lost in the greatest amount, from 100 to 900 lbs. of total N per acre, depending on ecosystem and fire characteristics (McNabb and Cromack 1990). Sulfur, phosphorus and other nutrients volatilize at higher temperatures than N, so losses to fire are typically much lower (McNabb and Cromack 1990).

Although total N can be lost in large quantities, the proportion of available N (primarily in the form of ammonium, nitrates, and amino acids) usually immediately rises (Haase and Sacket 1998, Driscoll et al. 1999, DeLuca and Zouhar 2000). This increase in available N often results in a decrease in fine root growth as less C is allocated to roots. Mycorrhizae may be completely eliminated (Wilcox 1991, Andersen and Rygiewicz 1991). Paralleling the reaction of fine roots, mycorrhizal development has been shown to increase when nutrients are limited (Trofymow and Vanden Driessche 1991, Ruehle et al. 1981). Such changes in nutrient capital and availability may be a factor in the observed increase in mycorrhizal formation in white pine with increases in fire severity (Herr et al. 1994).

It has been suggested that the successional stage of a forest and the time since disturbance dictates mycorrhizal species composition and their characteristics (Malajczuk and Hingston 1981, Allen 1991, Wilcox 1991). Earlier stages support a wider diversity of species that tend toward an r-selection response to stress while late successional stands support a narrower range of species that tend toward k-selection[2] (Last et al. 1987, also see Grime 1977). Older trees have also been found to be more likely to develop mycorrhizae in the duff and litter horizons (Parke et al. 1983, Harvey et al. 1978, Harvey et al. 1979). Species of mycorrhizae associated with different successional stages differ in their levels of sensitivity to fire (Cairney and Chambers 1999). For example, Schoenberger and Perry (1982) found that mycorrhizae associated with western hemlock, a late seral species, were sensitive to fire disturbance, while those supported by Douglas-fir, a relatively early seral species in the study area, were relatively resistant to fire. Thus, fire exclusion, which resulted in an under-representation of seral forest species, has also likely shifted composition of mycorrhizae towards less fire tolerant species (Cairney and Chambers 1999, Dix and Webster 1995). Furthermore, recolonization of heavily disturbed sites may favor species with above ground fruiting bodies or other mechanisms that promote early and/or long-range colonization.

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[2] r-selection strategists are relatively short lived, often early successional, have high reproductive rates, large number of offspring, and tend to be favored by unstable, disturbed, and rapidly changing environments. k-selection strategists are relatively long lived, late successional, have lower reproductive rates, smaller number of offspring, later maturation, and exist in relatively stable environments.

Host/Symbiont Interaction

Mycorrhizae require a living root system for their own long-term survival (Hacskaylo 1973, Harvey et al. 1980). The length of time their spores remain viable in the absence of a live host is not known, but may be as short as one year or less judging by recolonization rates following fire (Parke et al. 1984, Malajczuk and Hingston 1981, Harvey et al. 1980). Thus, fire may affect mycorrhizae indirectly through any damage to the host that ultimately impairs its root system. Damage to photosynthetic tissue can reduce carbon allocation to the roots and limit availability of carbohydrates. This reduces respiration potential and thus slows growth and maintenance processes (Nylund 1988). Bole damage can also limit growth potential of the root system. When the transport tissue becomes damaged and/or damage repair requires additional carbon, these resources are no longer available to the roots because shoots have a priority over roots in carbon allocation (Anderen and Rygiewicz 1991). Death can result if, for any reason, the tree cannot absorb (damage to roots), transport (damage to bole), or assimilate (damage to foliage) resources to maintain tissue, repair damage, or deal with stress (Dickinson and Johnson 2001).

Stress can also impair fine roots, mycorrhizae, or their host by making them more susceptible to insects and disease. When roots lose their ability to compartmentalize dead from live tissue, they are particularly sensitive to pathogens. Crown scorch or consumption may increase the host's susceptibility to attack from insects or disease by reducing the amount of assimilate needed to produce carbon-based defense mechanisms (bark, tannins, resins, terpenes).

Quantification of Fine Roots/Mycorrhizae

A variety of direct and indirect measures have been used to estimate damage to roots and/or mycorrhizae from fire. Examples include the amount of duff consumed and depth of char, dry weight of roots present in a soil sample, ocular counts of mycorrhizal root tips on exposed seedling roots, and surveys of above ground mycorrhizal fruiting bodies (Ryan 1982, Swezy and Agee 1991, Visser 1995, Herr et al. 1994, Parke et al. 1984). Damage to the roots of understory vegetation has been estimated by measuring the depth of reproductive organs and projecting their survival based on a theoretical model (Flinn and Wein 1977).

Analysis of soil cores is a fairly common and appropriate approach for estimating total fine root biomass, the proportion of living and nonliving roots, and the presence of mycorrhyzal fungi. Ocular assessments or staining procedures are used to differentiate fungal from non-fungal root tips (Swezy and Agee 1991, Ritter et al. 1989, Visser 1995, Harvey et al. 1978, Harvey et al. 1976, Buchholz and Gallagher 1982). However, root patterns, distribution, and coarse root biomass cannot be assessed reliably using soil cores (Vogt and Persson 1991).

As the soil core approach is labor-intensive in the field and lab, the development of site and species specific, easily measurable and reliable above-ground indicators of pre-fire and post-fire root biomass and/or mycorrhizal density would be useful for predicting the effects of fire on host health and recovery. Some indicators have been developed for this purpose, but they are site specific. Potential indicators include soil moisture, quantity of limiting nutrients, and plant carbohydrate levels (Vogt and Persson 1991). One study used root starch and soil temperature to indirectly approximate fine-root production (Marshal and Waring 1985). No known regression model of fine root or mycorrhizal growth or response to fire has been developed for central Idaho ponderosa pine forests at this time.

The study described here is part of a larger project designed to develop a mortality model for individual ponderosa pine and Douglas-fir trees following spring prescribed fire in Douglas-fir and ponderosa pine habitat types on the Boise National Forest. The proposed model will include both established and potentially less conventional prediction variables (Progar et al. 2002). The project described here focuses primarily on fine roots and mycorrhizae, but results may prove useful in developing regression equations that may be used in the mortality model for the larger project.

Materials and Methods

Study Area

The study area is located within the Danskin drainage approximately 12 miles East of Garden Valley on the Emmett District of the Boise National Forest, Valley County, Idaho. The legal description is T.9 N., R.5 E., sections 13 and 22-27 and T.9 N., R.6 E., sections 18-20 and 30, Boise Meridian.

The Danskin drainage is within the southwestern Idaho Boise Basin where the historical forest composition consisted mostly of ponderosa pine. The current mix of ponderosa pine and Douglas-fir or mostly Douglas-fir, believed to have occurred only rarely prior to the arrival of white Europeans, is a result of a century of fire suppression in an area where the historic fire interval was 10 to 22 years and fire intensities were low (Sloan 1998, Steele et al. 1986).

Study Design and Sampling Procedure

Burn perimeters were selected by USDA Forest Service land managers as part of an effort to restore fire to the study area to reduce accumulated fuels. Two zones (blocks) within the proposed burn perimeter were selected for sampling. Criteria for sampling site selection included the presence of both ponderosa pine and Douglas-fir in sufficient numbers (approximately 50 trees/hectare or more), and the high likelihood that the prescribed fire would carry through the stand. The later criterion was based primarily on fuel availability, aspect and expected fuel moistures. These criteria could only be met in primarily south facing bowls containing ponderosa pine stands with some component of Douglas-fir. One additional area with similar characteristics was selected to serve as a control block for the fine root and mycorrhizal study and received no treatment.

Six hundred sample trees were selected for the USDA Forest Service mortality study based on species and diameter at breast height (DBH). Sample trees were classified by DBH at 5.08 cm (2 in) intervals which included: 17.78 cm (7 in), 22.86 cm (9 in), 27.94 cm (11 in), 33.02 cm (13 in), 38.10 cm (15 in), 43.18 cm (17 in), 48.26 cm (19 in), 53.34 cm (21 in), 58.42 cm (23 in), and 63.50 cm (25 in) and greater. Each size class included trees with a DBH of within 2.54 cm (1 in) of a given class value. Visibly unhealthy trees and trees with obvious defects were excluded from the study. The plot center trees were permanently marked with tree paint and an aluminum identification tag.

Circular plots were established around each sample tree. Perimeters were delineated by standardized driplines based on DBH size class, with radii ranging between 3.44 m (11.3 ft) and 5.36 m (17.6 ft) from the exterior of the tree bole. Seven transects were established in each of the 2 treatment blocks and one transect in the control block. The point of origin of each transect was selected at random in each block and the direction to proceed from the point of origin was determined by field personnel based on the availability of sample species and size classes. Starting at the beginning of each transect, all ponderosa pine and Douglas-fir trees ≥ to 15.24 cm (6 in) DBH within 10.06 m (½ chain) on either side of each transect were automatically selected as sample trees in the order they were found until the 10 trees were selected for a given size class. Subsequently, no additional trees were selected within that size class. The plot radius was determined at each sample tree. Sample trees were selected such that plots did not overlap. In this larger project, the study of post-fire direct effects was limited to consideration of the influence of fuel, vegetation, and the topographic characteristics measured within the plot boundary. These independent variables were not evaluated in the study of fine roots and mycorrhizae.

In the study described here, subsets of approximately 30 plots per species (stratified random sample based on DBH) were selected in each of the treatment blocks and an additional 20 plots were established in a control block for root and mycorrhizal analysis. This study included three trees from each size class of each species in each treatment block and one of each size class per species in the control block. At each of 2 sample periods (one pre-burn and one post-burn), two soil cores were collected in each plot, one at the uphill canopy drip line and one at the half-way point between the dripline sample point and the bole of the plot center tree. In total, 56 soil cores were collected for Douglas-fir per sample period and 58 soil cores were collected for ponderosa pine per sample period.

Pretreatment cores were collected in October 2001. An impact driven soil-coring device[3], or "thumper", containing a removable clear plastic tube insert was used to extract soil profile (soil core) samples. The plastic sleeve inserts (38.1 cm long x 7.62 cm wide) served to retain the integrity of the cores during transport and storage. Cores were refrigerated at approximately 10ºC within 8 hours of extraction from the site. Drip line sample points and uphill directions were determined by ocular estimates; distance from the tree bole to the sample point was measured to the nearest 3.05 cm (1/10 ft). If an obstacle, such as a rock, occupied the designated sample point, the soil core was taken within a 30.48 cm (1 ft) radius of that point with a preference given to a point that appeared to be representative of the remaining plot. Length of the soil cores varied with the depth of the soil at the sample point; cores varied in the number and specific horizons they included. Immediately following core extraction from the ground, the organic and soil layers were identified through the plastic sleeve and marked to the nearest 0.5 cm on a strip of masking tape affixed to the sleeve. The horizons included litter, duff, shallow mineral soil (depth $\leq$10 cm), and deep mineral soil (depth >10 cm).

The prescribed burn took place on May 15th, 2002. Post-fire burn severity was categorized at each sample point as 'unburned', 'light', 'moderate', and 'deep' (Ryan 1982). "Unburned" meant that flames had not reached the sample point; "light" indicated partially consumed litter and duff; "moderate" indicated that duff and litter were completely consumed, or

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[3] Manufactured by Art's Manufacture & Storage (AMS) in American Falls, ID.

nearly so; "deep" indicated that duff and litter were consumed and the soil had been physically altered.

Two sub-sets of sample points (10% of the total for each species) were randomly selected for repeated sampling at two-month intervals following the burn treatment. The sample subsets included one plot for each species for each group of 3 adjacent size classes 17.78 to 27.94 cm (7-11 in), 33.02 to 43.18 cm (13-17 in), and 48.26 to 63.50 cm (19-25 in). A full set of post-treatment soil cores was collected in October 2002, approximately one year after pretreatment cores had been collected. This sampling schedule was designed to detect and distinguish seasonal variation from the treatment effect and to elucidate post-fire recovery patterns.

Laboratory Procedures

Soil horizon depths were recorded as marked on the tape when samples were collected. Each horizon was individually removed from the core sample for evaluation by applying gentle pressure from the top to push out the lowest (usually deep mineral soil) horizon first. Total weight of each horizon sample was recorded to the nearest 0.01 gram. All material in each horizon was then sieved in a standard 2mm sieve. A subsample of approximately 10 grams of the sieved material (less than 2 mm in diameter) from each horizon was placed in a small container, weighed, and oven dried for a minimum of 24 hours at 80ºC. Samples were reweighed (to the nearest 0.01 grams) and soil moisture was determined by subtracting the dry from the wet weight (without the weight of the container) and dividing this value (weight of the water) by the total wet weight and multiplying by 100.

All visible roots and accompanying mycorrhizae were removed from the sieve with tweezers, placed in plastic bags with about 50 ml of water and refrigerated. Sieved material was inspected for roots that may have passed through the sieve. If roots were found in sieved material they were included with the root sample for that horizon. Rocks $\geq$ 2mm (USDA class of ‘gravel’) remained on top of the sieve. This gravel was separated from any organic matter (eg. needles, leaves) and weighed to the nearest 0.01 grams.

The extracted roots were placed in a small container of water to remove any residual soil particles. Small soil clumps were gently crushed by hand in the water to facilitate root extraction. Once cleaned, roots were removed from the container with tweezers and refrigerated in a plastic bag with approximately 50 ml of water.

Mycorrhizal root tips were counted for each horizon by spreading root samples on a petri dish and viewing them through a dissecting microscope (10 to 50X). Any remaining soil particles or other organic matter was removed with tweezers. Active mycorrhizae were identified using visual cues according to Harvey et al. (1976). Each individual mycorrhizal root tip was included in the count, even if it was part of a more complex structure. Only root tips that were turgid and had a smooth surface were included in the tally. Viable mycorrhizal root tips included in the count were shades of browns, grays, and whites, and became lighter towards the distal end. Often, a web of fungal hyphae (hartig net) could be seen at maximum magnification. Root tips that were a single shade of dark gray to almost black, and appeared wrinkled and/or collapsed were considered inactive and were not counted. Although most mycorrhizal tips were identified with a high degree of confidence, about 5-6% were somewhat questionable. Nearly all mycorrhizal counts were made by the same person and the order in which the cores were processed was randomized to limit systematic bias. No attempt was made to identify roots or mycorrhizae by species.

Living roots were distinguished and separated from dead roots according to modified guidelines from Visser (1995). Turgid and plump roots that could not easily be pulled apart with tweezers were counted as live. Those that were black and shriveled in appearance, became waterlogged readily, and broke apart easily with tweezers were considered dead. Roots were placed in separate folded paper towels, oven dried (24 hours at 80ºC) and then weighed to the nearest 0.01 gram according to Vogt and Persson (1991). Roots greater than 0.7 cm in diameter were weighed separately. This diameter was selected to closely match the threshold size used to define fine roots in similar research.

Volume of each horizon was estimated (to the nearest 0.01 liter) using the plastic sleeve diameter (7.62 cm) and horizon depth (to the nearest 0.5 cm) so that biomass of fine roots and density of mycorrhizal root tips could be calculated per liter of soil. A standard formula for calculating the volume of a cylinder was used (πr^2 x height). This value was divided by 1,000 to convert to volume in liters. Soil bulk density could be calculated by dividing the volume by the oven dry weight of each horizon. Fine root biomass and mycorrhizal densities were obtained by dividing the dry weight of roots and mycorrhizal root tip count by the volume (liters) of the horizon.

About 15-20 hours before the burn, litter, duff, and shallow mineral soil were sampled from a point 1.83 m (6 ft) uphill from the tree bole in each plot. Samples were immediately weighed to obtain wet weight, and then oven dried at 60°C for 24 hours to obtain the dry weight (to the nearest 0.01 g) so moisture content could be determined. Due to errors in sample collection, litter and duff moisture data were unusable. Moisture content of the mineral soil, however, was used in analysis.

Changes in fine root biomass and mycorrhizal densities were calculated for samples from burned areas (those categorized as light or moderate during sample collection) when ANOVA indicated there was a significant difference in biomass or densities between pre- and post-fire samples. These values were calculated by subtracting the post-fire weight or count per liter from the pre-fire weight or count per liter. Reductions in litter and duff depths were similarly calculated. The ‘total consumption of organic horizons’ was calculated as the sum of the reductions of litter (cm) and duff (cm). ‘Total residual organic depth’ was calculated as the sum of the depths of the post-fire duff (cm) and litter (cm). 'Total pre-burn organic depth' was calculated as the sum of the pre-burn depths of duff (cm) and litter (cm).

Statistical Analyses

Distributions of the data were checked for normality prior to further analyses. Because fine roots and mycorrhizae were absent in a large proportion of the litter and duff horizons, the data tended to be bimodally distributed and data in all horizons were consistently positively skewed, thus violating the assumptions of the analysis of variance. A log transformation was thus applied to fine root biomass and mycorrhizal densities in each horizon.

[1] $X_1 = \log(X+1)$

Where X = individual fine root or mycorrhizal density value.

Data on rock weight/l were similarly transformed to meet assumptions for Pearson's Correlation analysis (see Appendix G and F). Tests of normality indicated transformations were not necessary for bulk density, total organic reduction, residual organic depth, soil moisture, or fine root and mycorrhizal reductions.

A factorial ANOVA using a general linear model program (SAS) was used to assess differences in mean fine root biomass and mycorrhizal densities. Main effects included horizon (pre-fire), sample period, burn severity class, DBH size class (pre-fire), and sample position (pre-fire) for Douglas-fir and ponderosa pine. Analysis of pre-fire data focused on distribution and patterns of fine root biomass and mycorrhizal densities and differences associated with species, DBH, sample position within plot, total organic depth, and burn severity classes. Separate ANOVA's were also conducted by horizon and species for the entire pre-fire sample period.

Data for post-fire analysis were grouped by severity class and sample period. When ANOVA's detected significant differences, Fisher's protected LSD was used to compare fine root biomass and mycorrhizal densities as follows.

Pre-fire comparisons 1) All horizons within species.
2) All like horizons by DBH class and sample position within species.
3) All like horizons by severity class and species.
Post-fire comparisons 1) All like horizons by severity class and sample period within species.

When Fisher's LSD indicated that one or more multiple comparisons were significantly different and a linear pattern between factors was apparent, Pearson's correlation matrices were developed (using SAS) to determine whether the data would be useful in predictive modeling. For each species, variables in the correlation matrices included fine root biomass, mycorrhizal densities, bulk density, duff/litter depth, rock weight (>2mm), duff/litter consumption, residual duff/litter depth, reduction in fine root biomass, and reduction in mycorrhizal density. When correlations were statistically significant, regression analyses were used (SAS) to fit the best combinations of independent variables to predict pre-fire fine root biomass and mycorrhizal densities and reductions in biomass and densities in response to prescribed fire.

Results

The prescribed burn took place on May 15, 2002. On the day of the burn, winds were calm, ambient air temperature was 16º C, and relative humidity was 25 percent. Fuel moistures were approximately 4 to 5 percent for 1 hour fuels, 7 to 9 percent for 10 hour fuels, 12 to 15 percent for 100 hour fuels, 15 to 18 percent for 1,000 hour fuels, 25 to 30 percent for 10,000 hour fuels, and duff moisture was between 80 and 110 percent.

Due to the patchy and unpredictable nature of the prescribed burn, more than 60% of the sample sites in the treatment blocks were unburned after the prescribed fire (Tables 2, 3 and Appendix A). Flame reached only 14 of the 56 Douglas-fir sample points in the treatment blocks and only 24 of the 58 sample points for ponderosa pine sites. Only 7 of these sample sites showed evidence of 'moderate' burn severity, all of them associated with ponderosa pine plots. No 'deep' burn severities were recorded at any sample point. Some of the pre-fire comparisons and most of the post-fire comparisons are classified by post-fire severity class. The two 10% subsamples were excluded from most analyses because of small sample sizes and problems meeting parametric assumptions. Averages, standard deviations, and proportions burned for each soil horizon are provided in Appendix A.

Pre-fire Comparisons

Mean pre-fire fine root biomass was significantly different between horizons for each species ($p < 0.05$), except between shallow and deep mineral soil (Appendix B). The highest pre-fire mean biomass of fine roots was found in the shallow and deep mineral soil for both Douglas-fir (2.39 and 2.26 g/l, respectively) and ponderosa pine (1.79 and 2.05 g/l, respectively) (Table 2). Mean weight of fine roots was significantly lower in duff and litter horizons for both Douglas-fir (1.26 and 0.22 g/l, respectively) and ponderosa pine (1.26 and 0.10 g/l, respectively) (Appendix A, B).

Mean pre-fire mycorrhizal densities were significantly different between all horizons for both species (Appendix B). The highest mean mycorrhizal density occurred in the shallow mineral soil of both Douglas-fir (74.33/l) and ponderosa pine (74.01 /l) followed in rank by the deep mineral soil (26.34 and 48.62/l respectively), duff (19.61 and 11.07/l respectively), and litter (3.82 and 1.98 respectively) (Table 3 and Appendix A, B). Since treatment blocks did not burn uniformly, pre-fire data were analyzed by post-burn severity class of the area from which the samples were extracted. Tables 2, 3, Figures 1 through 10, and Appendices A through D show mean fine root biomass and mycorrhizal pre-fire densities by species, size class, sample position, soil horizon, and burn severity.

Litter Horizon

Three of four comparisons by DBH class of mean pre-fire biomass of fine roots and mycorrhizae within the litter horizon were not significantly different between DBH size classes or sample positions (dripline or halfway point) (Figures 1-4 and Appendix C). The exception was ponderosa pine fine root biomass by DBH class ($p = 0.03$). Despite statistically significant differences, no linear relationship was apparent between mean fine root biomass of ponderosa pine and tree diameter (Figure 2 and Appendix C). Only a small percentage of litter samples contained any fine roots (16% for Douglas-fir and 18% for ponderosa pine) or mycorrhizae (5% for Douglas-fir and 3% for ponderosa pine) (Appendix A). When mean pre-fire fine root biomass and mycorrhizal densities in the litter horizon were grouped by post-fire severity classes and species, no significant differences were found (Figures 5-6 and Appendix D).

Duff Horizon

Analysis by DBH and sample position did not reveal any statistically significant differences in mean fine root biomass and mycorrhizal densities (Figures 1-4 and Appendix C). Pearson's correlations with site variables (rock weight, bulk density, duff and litter depth) showed a weak, but significant correlation ($r = 0.24$, $p = 0.05$) between mycorrhizal density and bulk density of the duff horizon for Douglas-fir (Figure 7 and Appendix F). Fine root biomass of ponderosa pine samples were also significantly correlated with bulk density of the duff ($r = 0.29$, $p = 0.02$) (Figure 8). Root biomass of Douglas-fir was correlated with the depth of this horizon ($r = 0.26$, $p = 0.03$) (Figure 9 and Appendix F) and mycorrhizal density was near significance with depth ($r = .23$, $p = .06$) (Appendix F).

Analysis of pre-fire samples by species and post-fire severity classes showed no significant differences among either pre-fire fine root biomass or mycorrhizal mean densities (Figures 5, 6 and Appendix D).

Table 1. Probability values of ANOVAs for tests of variation in fine root biomass and mycorrhizal densities by soil horizon and species for post-burn severity class and sample time period.

	Soil Horizon			
	Litter	Duff	SMS	DMS
Douglas-fir				
Fine Roots				
Severity	0.03	0.73	0.75	0.01
Sample Period	0.01	0.2	0.21	0.51
Interaction	<0.01	0.41	0.01	0.10
Mycorrhizae				
Severity	0.54	0.89	0.45	0.58
Sample Period	0.35	0.02	<0.01	0.06
Interaction	0.81	0.54	0.01	0.05
Ponderosa pine				
Fine Roots				
Severity	0.66	0.59	0.87	0.97
Sample Period	0.75	0.47	<0.01	0.78
Interaction	0.45	0.52	0.4	0.39
Mycorrhizae				
Severity	0.97	0.68	0.03	0.06
Sample Period	0.83	0.37	<0.01	0.8
Interaction	0.46	0.28	0.12	0.27

Table 2. Mean fine root biomass (g/l) and mycorrhizal densities (root tips/l) in pre- and post-fire Douglas-fir soil core samples by treatment block and soil horizon. P-values are provided for comparisons between pre-and post-fire conditions. Standard deviations are provided in parentheses.

			Fine Roots			Mycorrhizae		
Block/Severity	Horizon	N	Pre-fire	Post-fire	p-value	Pre-fire	Post-fire	p-value
Control/	Litter	20	0.10	0.09	0.90	1.16	0.00	0.46
Unburned			(0.33)[3]	(0.35)		(5.20)[3]	(0.00)	
	Duff	15-20	0.80	1.89	0.73	11.32	3.88	0.23
			(1.10)	(4.82)		(25.44)	(15.02)	
	SMS[1]	20	1.67	8.84	0.07	113.06	35.13	0.05
			(0.93)	(24.06)		(118.15)	(45.70)	
	DMS[2]	17-20	1.94	1.79	0.30	41.47	41.13	0.42
			(1.02)	(1.99)		(54.65)	(60.48)	
Burn blocks/	Litter	37-40	0.13	0.09	0.44	6.40	0.25	
Unburned			(0.31)	(0.53)		(29.78)	(1.53)	0.14
	Duff	27-36	1.09	0.63	0.19	15.24	4.58	0.37
			(1.91)	(1.35)		(41.82)	(11.20)	
	SMS	38-41	2.43	2.11	0.24	47.95	37.16	0.67
			(1.72)	(2.15)		(61.73)	(33.95)	
	DMS	31-34	2.21	2.96	0.03	15.51	36.69	<0.01
			(1.47)	(1.51)		(16.98)	(36.70)	
Burn blocks/	Litter	7-13	0.00	2.87	<0.01	0.00	0.00	1.00
Light			(0.01)	(6.90)		(0.00)	(0.00)	
	Duff	9-14	2.30	0.34	0.19	42.10	0.25	0.07
			(6.40)	(0.93)		(89.25)	(0.74)	
	SMS	14	3.30	1.20	0.01	96.24	19.85	<0.01
			(2.24)	(1.20)		(135.34)	(26.05)	
	DMS	10-12	2.92	3.08	0.66	31.81	71.28	0.14
			(1.94)	(1.53)		(31.64)	(108.57)	

[1] Shallow mineral soil

[2] Deep mineral soil

[3] Standard deviation

Table 3. Mean fine root biomass (g/l) and mycorrhizal densities (root tips/l) in pre- and post-fire ponderosa pine soil core samples by treatment block and soil horizon. P-values are provided for comparisons between pre-and post-fire conditions. Standard deviations are provided in parentheses.

			Fine Roots			Mycorrhizae		
Block/Severity	Horizon	N	Pre-fire	Post-fire	p-value	Pre-fire	Post-fire	p-value
Control/ Unburned	Litter	19-20	0.00 (0.00)	0.31 (0.00)	0.24	0.00 (0.00)	13.06 (56.93)	0.23
	Duff	18-20	1.51 (3.15)	3.10 (7.11)	0.6	2.32 (10.40)	183.52 (635.73)	0.42
	SMS[1]	20	1.43 (0.83)	1.38 (1.29	0.63	123.53 (154.03)	50.20 (70.41)	0.01
	DMS[2]	16-20	1.77 (1.01)	3.68 (8.03)	0.30	42.55 (50.89)	68.06 (66.95)	0.08
Burn blocks/ Unburned	Litter	27-34	0.25 (0.76)	1.38 (6.48)	0.58	4.10 (23.94)	0.86 (4.48)	0.89
	Duff	12-26	1.56 (2.49)	1.85 (4.98)	0.58	19.37 (68.16)	2.91 (10.07)	0.23
	SMS	33	1.91 (1.69)	2.54 (8.25)	0.13	51.95 (60.70)	65.68 (135.65)	0.20
	DMS	26	2.28 (1.31)	1.73 (1.00)	0.18	54.95 (78.49)	68.92 (88.14)	0.19
Burn blocks/ Light	Litter	17	0.33 (1.16)	0.00 (0.00)	0.47	0.79 (3.17)	0.00 (0.00)	0.63
	Duff	3-14	0.72 (0.75)	0.00 (0.00)	0.35	8.32 (16.90)	0.00 (0.00)	0.34
	SMS	17	1.86 (1.33)	1.03 (1.67)	0.02	73.47 (109.59)	4.52 (7.42)	<0.01
	DMS	11-12	2.02 (1.79)	2.09 (1.72)	0.99	36.23 (42.73)	27.44 (41.24)	0.78
Burn blocks/ Moderate	Litter	0-7	0.38 (1.00)	0.00 (0.00)	1.00	0.00 (0.00)	0.00 (0.00)	1.00
	Duff	0-7	0.54 (0.71)	0.00 (0.00)	1.00	10.71 (15.10)	0.00 (0.00)	1.00
	SMS	7	3.54 (3.84)	0.79 (0.35)	0.07	37.89 (30.50)	12.30 (12.43)	0.12
	DMS	5-6	2.04 (1.83)	2.35 (1.79)	0.65	69.72 (78.73)	25.13 (36.62)	0.31

[1] Shallow mineral soil

[2] Deep mineral soil

[3] Standard deviation

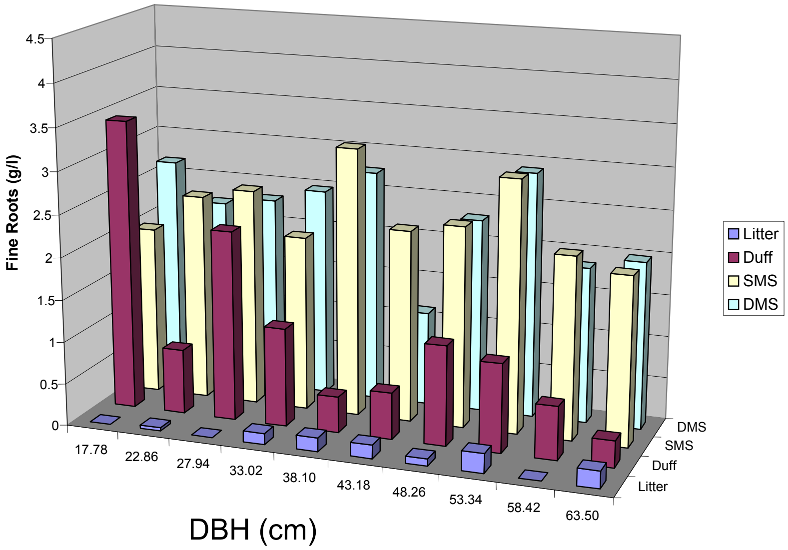

Figure 1. Mean fine root weight (g/l) by soil horizon and DBH size class of Douglas-fir for the pre-fire sampling period. No statistically significant differences (p = 0.05) were found between means by DBH size classes in any horizon.

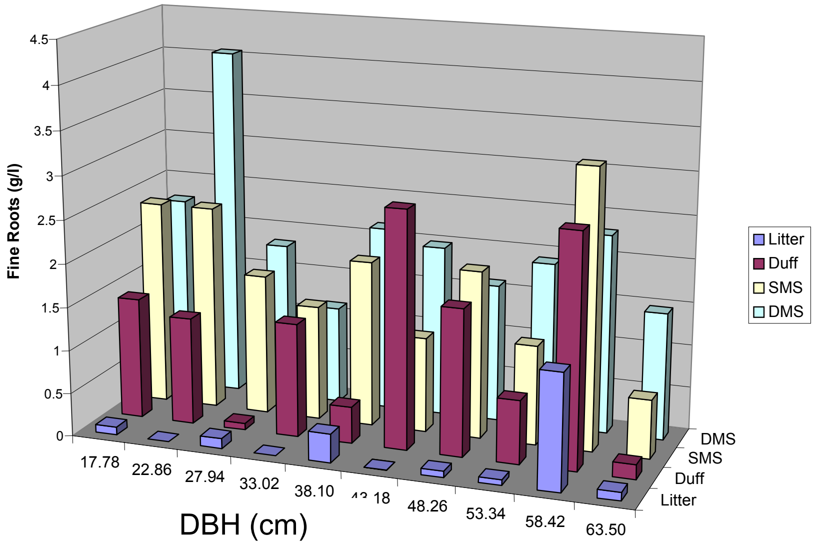

Figure 2. Mean fine root weight (g/l) by soil horizon and DBH size class of ponderosa pine for the pre-fire sampling period. Statistically significant differences (p = 0.05) in mean biomass were found between DBH size classes in the litter and shallow mineral soil, but no linear pattern between these variables is evident (see appendix C).

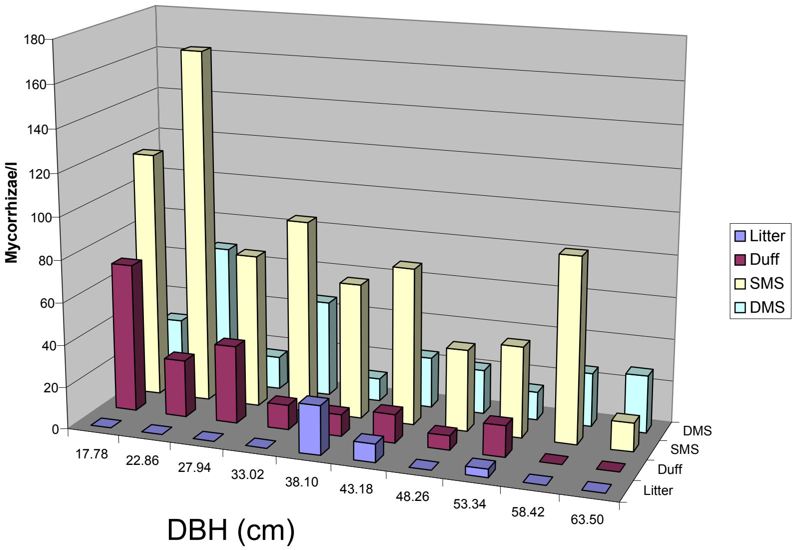

Figure 3. Mean mycorrhizal root tips per liter by soil horizon and DBH size class of Douglas-fir for the pre-fire sampling period. No statistically significant (p = 0.05) differences were found by DBH size classes and no linear pattern is apparent.

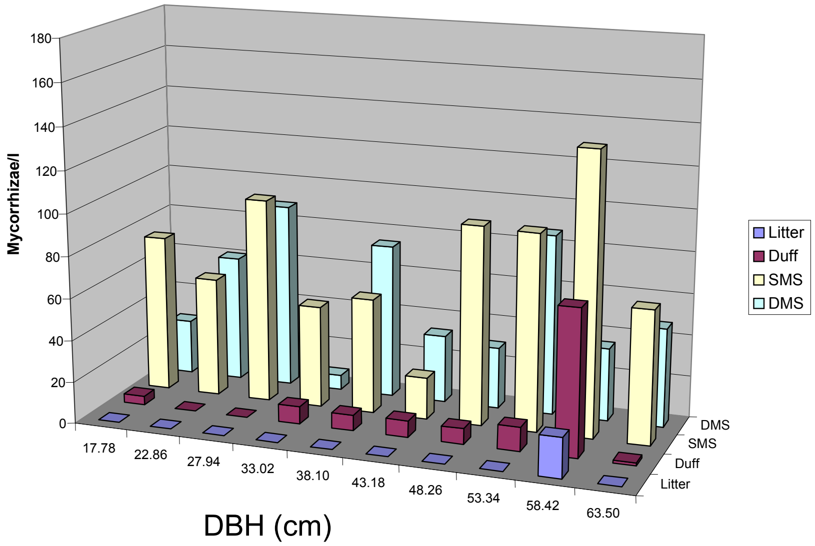

Figure 4. Mean mycorrhizal root tips per liter by soil horizon and DBH size class of ponderosa pine for the pre-fire sampling period. Statistically significant differences (p = 0.05) in mean densities were found by DBH size class only in the deep mineral soil, but no linear pattern is evident (see appendix C).

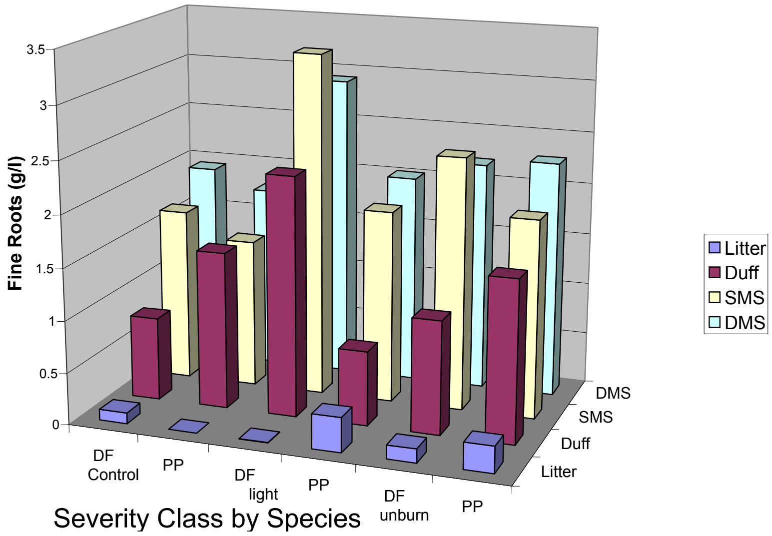

Figure 5. Pre-fire fine root weight (g/l), by tree species, and post-fire burn severity class for each horizon. In shallow mineral soil, Douglas-fir had significantly higher biomass (2.47 g/l) than ponderosa pine (1.82 g/l). No statistically significant (p = 0.05) differences were found between means by severity classes.

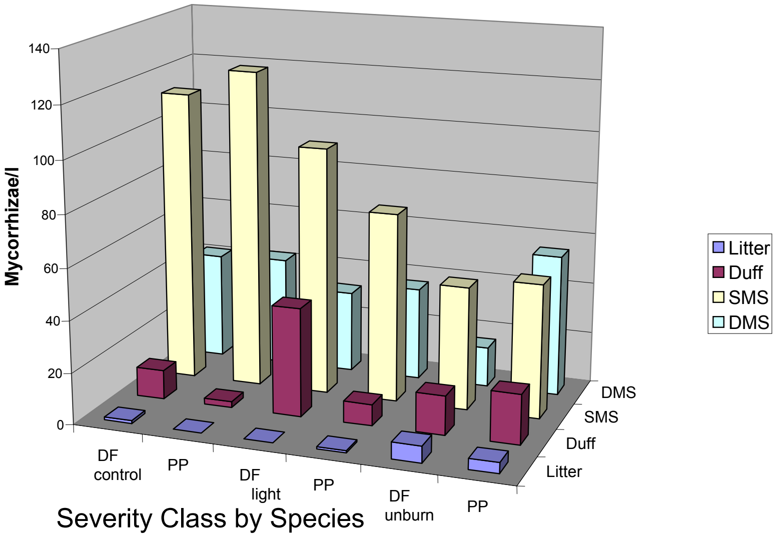

Figure 6. Pre-fire mean mycorrhizal density per liter, by tree species, and post-fire burn severity class for each horizon. There were statistically significant (p = 0.05) differences between severity classes in mean mycorrhizal density in the shallow mineral soil of ponderosa pine between the control and unburn groups. Species were not significantly different.

Shallow Mineral Soil Horizon

With one exception, no statistically significant differences were found in average biomass of fine roots and densities of mycorrhizae in the shallow mineral soil horizon analyzed by DBH class and sample position. Mean fine root biomass of ponderosa pine were significantly different by DBH class (Figure 2 and Appendix C). Fisher's LSD showed significantly lower fine root biomass in the 63.50 cm (25 in) size class compared to all other size classes, and the highest biomass of fine roots in the 58.42 cm (23 in) size class (Figure 2 and Appendix C). Again, no linear relationship was evident (Figure 2).

A significant correlation ($r = 0.33$, $p = 0.01$) was found between fine root biomass for Douglas-fir plots in shallow mineral soil and the total organic depth (see methods) above this horizon (Figure 10 and Appendix F). A regression equation predicted fine root biomass in shallow mineral soil for undisturbed Douglas-fir plots based on the total organic depth ($p < 0.01$).

[2] $Y' = 0.3270 + (0.0284)(y_1)$

Where y_1 = the total organic depth = litter depth (cm) + duff depth (cm)

and Y' = fine root biomass

The mean of pre-fire fine root biomass of Douglas-fir samples (2.47 g/l) was significantly higher than ponderosa pine samples (1.82 g/l, $p = 0.02$) in shallow mineral soil. When classified by post-fire burn severity, groups were significantly different from each other in pre-fire mean mycorrhizal density ($p = 0.05$), but differences between species were not significant (Figure 5 and Appendix D). Fisher's LSD indicated a significant difference between species for mean fine root biomass ($p = .03$) (Figure 5) and between control and unburn classes for mycorrhizal density ($p = 0.01$) (Figure 6).

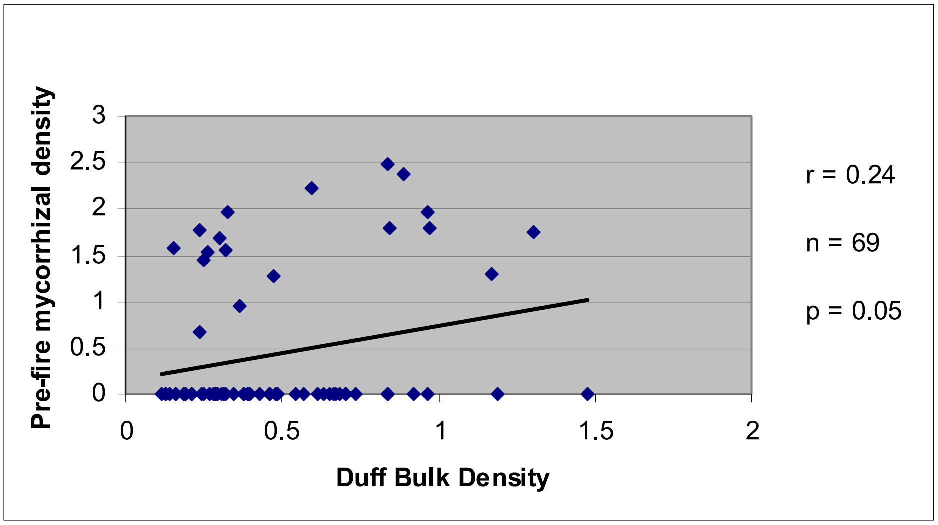

Figure 7. Pre-fire mycorrhizal density (root tips/l) in the duff horizon of Douglas-fir by the bulk density of the duff. Raw data were transformed by log(X+1).

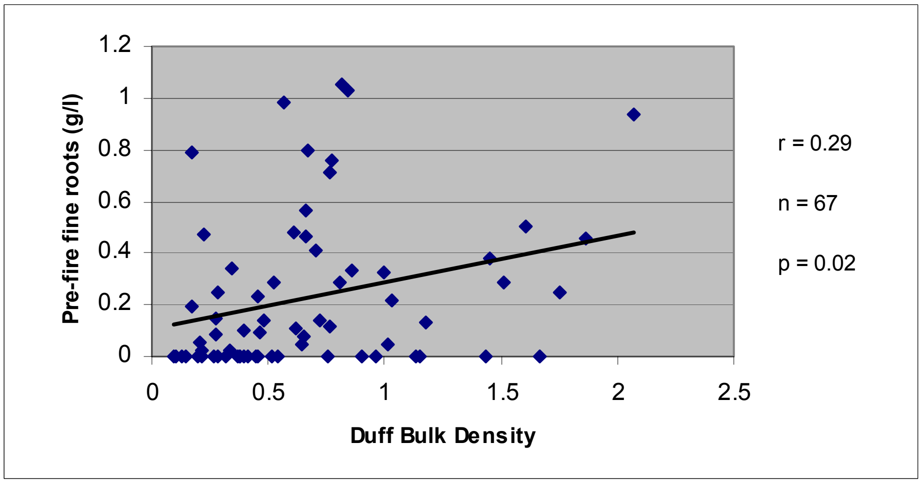

Figure 8. Pre-fire fine root biomass (g/l) in duff and bulk density of duff for ponderosa pine. Raw data were transformed by log(X+1).

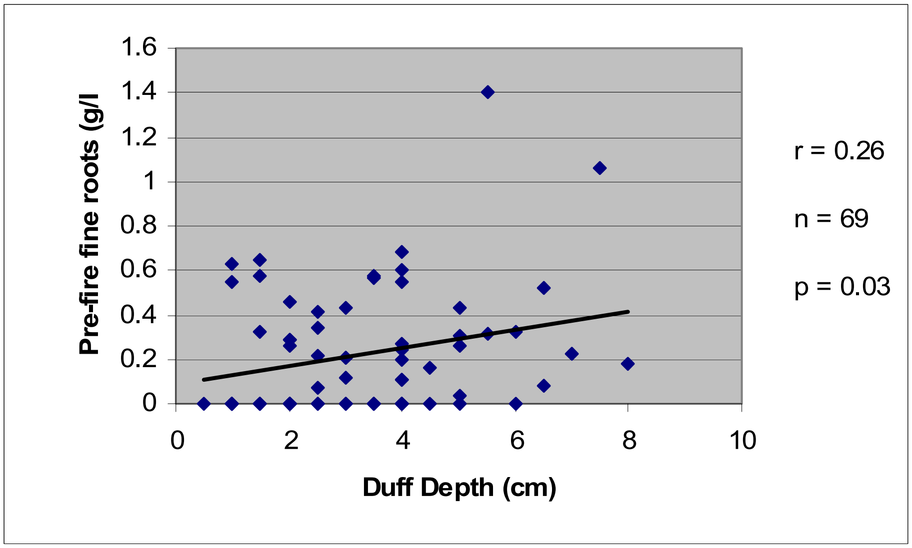

Figure 9. Pre-fire fine root biomass (g/l) in the duff of Douglas-fir and depth of the duff (cm). Raw data were transformed by log(X+1).

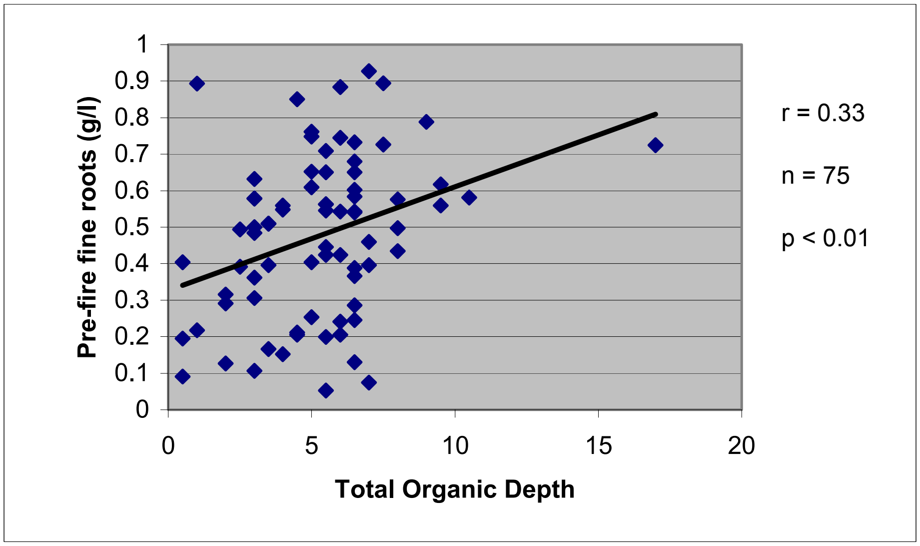

Figure 10. Pre-fire fine root biomass (g/l) in shallow mineral soil of Douglas-fir and total organic depth (cm). Raw data were transformed by log(X+1).

Deep Mineral Soil Horizon

When deep mineral soil samples were classified by DBH size class and sample position for each species, significant differences were found only in mean mycorrhizal densities among DBH classes of ponderosa pine. Fisher's LSD showed significant differences among size classes, but no linear pattern was detected (Figures 1-4 and Appendix C).

No significant correlations were found between the fine root biomass and mycorrhizal densities and site conditions (Appendix F). When samples were classified by species and post-fire severity class, ANOVA indicated no significant pre-fire differences for fine root biomass and mycorrhizal mean densities (Appendix D).

Post-fire Comparisons and Fire Effects

Litter Horizon

Significant differences were found between mean fine root biomass of Douglas-fir for both sample period and post-fire severity class in litter (Table 1 and Appendix E). This result was due to an increase in fine root biomass of only 2 of 13 samples in the light severity class following the burn and was not a generalized result associated with the treatment.

Since the changes in fine root biomass and mycorrhizal densities did not appear to be generally associated with the treatment, correlation coefficients were not calculated between fine root biomass and mycorrhizal density reductions and indicators of fire effects (organic consumption, residual organic depth).

Duff Horizon

Mean Douglas-fir mycorrhizal densities decreased in all severity classes between sample periods ($p = 0.02$). Treatment group was not a significant factor in the ANOVA (Appendix E). No other differences in fine root biomass or mycorrhizal densities were statistically significant (Appendix E).

Since the changes in fine root biomass or mycorrhizal densities did not appear to be associated with treatment, correlation coefficients with fire effects indicators (organic reduction, residual organic depth) were not calculated for this horizon.

Shallow Mineral Soil Horizon

Analysis of shallow mineral soil samples categorized by post-fire burn severity class and sample period showed multiple significant differences in fine root biomass and mycorrhizal densities for each species (Tables 1, 2, 3 and Appendix E).

Fisher's LSD showed significant reductions in mean fine root biomass in the light severity class in the post-burn sample period compared to pre-burn ($p = 0.01, 0.02$ for Douglas-fir and ponderosa pine, respectively), while mean biomass in the control and unburn classes did not significantly change between sample periods. Fine root biomass in the moderate burn class in ponderosa pine also decreased between sample periods; the change was near, but not statistically significant ($p = 0.07$) (Table 3).

Mean mycorrhizal densities were lower following fire than the pre-fire densities in the light burn severity class for both Douglas-fir ($p < 0.01$) and ponderosa pine ($p < 0.01$). However, they were also lower for the control group in the sample period following fire for both Douglas-fir ($p = 0.05$) and ponderosa pine ($p = 0.01$). Post-fire, mycorrhizal densities were significantly lower in the light burn category than in the control for ponderosa pine ($p = 0.01$), but not for Douglas-fir ($p = 0.09$). Although mycorrhizal densities in the moderate burn class in ponderosa pine were lower following the burn, this reduction was not statistically significant ($p = 0.12$) (Table 3 and Appendix E). Since the reduction was similar to that in the light burn class (which was statistically significant), it is likely that small sample size affected the statistical significance of the result.

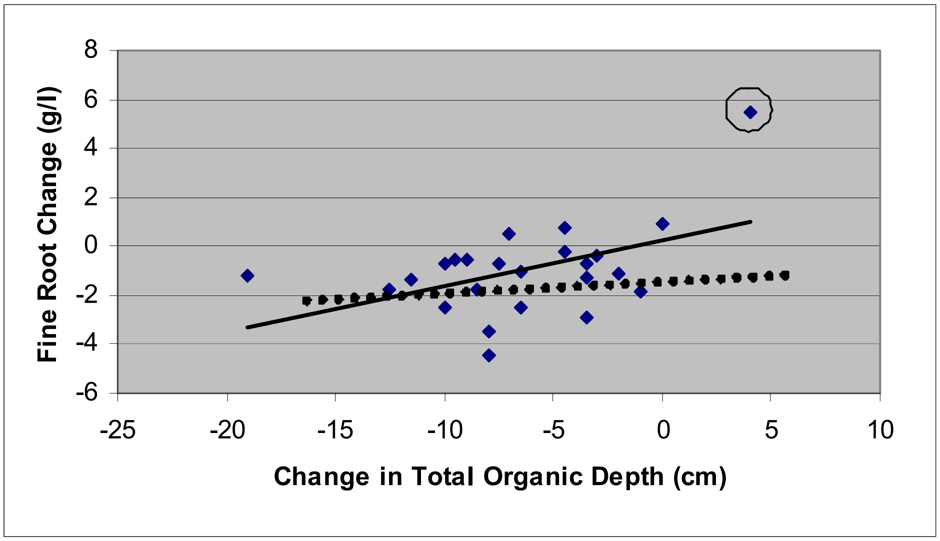

Figure 11. Change in fine root biomass (g/l) in shallow mineral soil of ponderosa pine by the total change in organic depth (cm) following light and moderate burn severity treatment (r = 0.48, p = 0.02). The solid and dotted lines represent the least square means with and without the circled outlier, respectively. The r-value refers to analysis that includes the outlier.

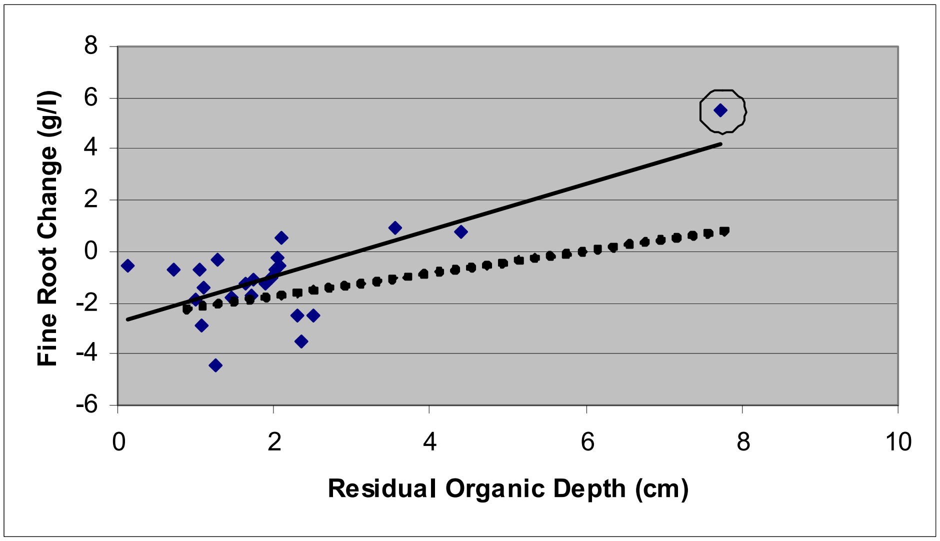

Figure 12. Change in fine root biomass (g/l) in shallow mineral soil of ponderosa pine by the residual organic depth (cm) following light and moderate burn severity treatment (r = 0.73, p < 0.01). The solid and dotted lines represent the least square means with and without the circled outlier, respectively. The r-value refers to analysis that includes the outlier.

Strong correlations were found between fine root biomass change (burned plots only) in shallow mineral soil of ponderosa pine plots and both total organic consumption ($r = 0.48$, $p = 0.02$) (Figure 11) and residual organic depth ($r = 0.72$, $p < 0.01$) (Figure 12 and Appendix G). A regression equation was fit ($p < 0.01$) to predict fine root biomass reduction (Y') using these variables,

[3] $Y' = 2.0900 + 0.0779(x_1) + (-0.7948)(x_2)$

where x_1 = the total organic reduction (cm) between sample periods

and x_2 = the residual organic depth (cm) following the treatment.

Deep Mineral Soil Horizon

Sample period (pre-fire vs post-fire) and burn severity class were significant factors in the differences in the fine root biomass of Douglas-fir and mycorrhizal densities of ponderosa pine ($p = 0.01$ and 0.03 respectively) (Tables 1, 2, 3 and Appendix E). However, Fisher's LSD multiple comparisons indicated that differences did not seem to be associated with treatment (ie. changes were not seen in the treatment group while the control was constant), but appeared random or due to unknown effects.

Since changes in the deep mineral soil horizon did not appear to be related to sample period or burn severity class, no further analyses were conducted.

Discussion

These analyses support prior findings that fine roots associate differently with different tree species and tree species themselves react differently to fire (Herr et al. 1994, Schoenberger and Perry 1982, Flint 1925). Because the roots in the core samples were not identified by species, it is possible that roots from another tree or woody plant species were present in some cores. However, since the majority of its roots can be found beneath an individual tree's dripline, and few understory plants were present at the study sites, it is likely the samples included primarily roots from the plot center trees.

Pre-fire Comparisons

In the pre-fire sample period, ponderosa pine and Douglas-fir samples did not differ significantly in mycorrhizal densities (Appendix D). For both species, mycorrhizal density was highest in the mineral soil fractions and lower in duff and litter (Tables 2, 3 and Appendix B). This finding contrasts with most published research that suggest mycorrhizal densities are highest in organic substrates in forest ecosystems (Harvey et al. 1976, Harvey et al. 1978, Harvey et al. 1980, Reddell and Malajczek 1984). This finding of lower mycorrhizal densities in organic layers may be a response, or adaptation to, the historically high fire frequencies or other disturbances in the study area. Malajczuk and Hingston (1981) found that density of mycorrhizal species associated with organic horizons decreased as fire frequency increased. Visser (1995) noted that most mycorrhizae in his study sites were in mineral soil, except in an old growth stand that received little disturbance, providing further evidence of the tendency of mycorrhizae to inhabit organic substrates only when extended disturbance-free periods occur. It is possible that our study area supported primarily those species of mycorrhizae adapted for non-organic soil fractions since those found in organic fractions were continuously removed by fire or were sloughed off on the steep slopes.

Fine root biomass was also highest in mineral soil horizons (Appendix B). In the pre-fire sample period, ponderosa pine had significantly greater mean fine root biomass in the shallow mineral soil than Douglas-fir (Appendix D). Although not statistically significant, ponderosa pine had a higher proportion of fine roots in deep mineral soil (53%) while Douglas-fir had a higher proportion in the shallow mineral soil (51%). This difference between species makes sense since, Douglas-fir tends to have shallower root systems than does ponderosa pine (Starker 1934).

We expected to find increases in fine root biomass and mycorrhizal density with increases in plot tree diameters because accumulation of organic debris is generally highest under larger diameter trees and fine roots and mycorrhizae have been found to be associated with organic substrates (Ryan and Frandsen 1991, Harvey et al. 1976, Harvey et al. 1978). However, pre-fire fine root biomass and mycorrhizal densities did not appear to be linearly related to DBH size class. It is possible that aspect, canopy closure, soil moisture or other variables were more important in determining fine root biomass and mycorrhizal density than tree size.

Ryan and Frandsen (1991) found that duff and litter depths tended to increase with proximity to the tree bole in mature ponderosa pine stands. Thus we expected to find more fine root biomass and higher mycorrhizal density in the samples collected at the half-way point than the samples collected at the dripline. However, distance from tree bole was not a significant factor in the distribution of fine roots and mycorrhizae in the current study. Since most of the fine roots and mycorrhizae were in mineral soil layers, it is possible the build-up of organic horizons did not strongly influence the two variables and that aspect, canopy closure, soil moisture or other variables were more important in determining these values than proximity to the tree bole. It is also possible that due to the steep slopes, duff and litter were more evenly distributed across the plots. In addition, the general absence of fine roots and mycorrhizae in the duff and litter may reflect high temperatures and low moisture at the surface in this hot and dry ecosystem.

Ideally, mean biomass of fine roots and density of mycorrhizae would be similar in pre-fire (treatment) groups. Significant differences in pre-fire groupings based on post-fire severity classes are of particular concern since the ability to detect main effects can be compromised. However, in only one case did ANOVA detect significant pre-fire differences in mean density of mycorrhizae in shallow mineral soil when grouped by post-fire severity classes (Appendix E). Since this particular difference occurred between the control and the unburned area, it did not interfere with our ability to detect changes based on treatment. And because the unburned areas in the treatment blocks did appear to be different than the control blocks, they were kept separate in subsequent analyses. It is possible that the unburned severity class shared a characteristic that both differentiated mean mycorrhizal density and created a propensity to not burn (eg. aspect, canopy coverage, duff moisture, etc.). No other significant differences were detected between samples in pre-burn groupings based on post-burn severity classes. This is a good indication that other pre-treatment groupings were ecologically comparable to each other, an important assumption in time series research of any kind.

Correlations between fine root biomass and mycorrhizal densities and other site conditions were statistically significant in only four cases: 1) mycorrhizal density of Douglas-fir in duff with duff bulk density, 2) fine root biomass of ponderosa pine in duff with duff bulk density, 3) fine root biomass of Douglas-fir in duff with duff depth, and 4) fine root biomass of Douglas-fir in shallow mineral soil with the total organic depth (litter depth + duff depth). Thus, two important similarities can be seen: a relationship with the amount (depth) of organic material, and with the porosity (bulk density) of the duff. Curiously, bulk density was not a factor in mineral soil horizons for either fine root or mycorrhizal densities (Appendix F). Soil bulk density has been associated with fine root biomass and mycorrhizal densities in other research (DeByle 1981, Brady and Weil 1999, Voorhees et al. 1971, Voorhees et al. 1975, Harvey et al. 1976). The presence and amount of organic material has also been linked to mycorrhizal densities in other research (Harvey et al 1978, Harvey et al. 1979, Harvey et al. 1976). In this study, data were sufficient to fit a regression equation based on organic depth that can reasonably estimate fine root biomass in shallow mineral soil associated with Douglas-fir. This model may prove useful to managers interested in sustaining the below ground ecosystem.

Post-fire

In anticipation of the patchy and unpredictable nature of prescribed burning, more soil cores were sampled than the estimated minimum necessary to make useful comparisons. Nonetheless, an unexpectedly high number of sample points in the treatment blocks remained unburned, particularly those associated with Douglas-fir (Appendix A), thus limiting the possibility of testing certain hypotheses. For example, fine root biomass and mycorrhizal density comparisons in the litter horizon were excluded from correlation analyses for this reason. The disproportionately small number of burned samples associated with Douglas-fir trees (compared to the ponderosa pine sample) likely reflects their more frequent occurrence in locations with higher moisture levels and qualities of needle cast (such as packing ratio) that make them less likely to carry or sustain a flame front than the needle cast of ponderosa pine (Agee 1993).

Although litter and duff were commonly reduced on burned sample points, significant reductions in mean fine root biomass and mycorrhizal densities due to the treatment were rare in these horizons. For the most part, this result reflects a general absence of fine roots and mycorrhizae in these layers in the pre-fire phase of sampling (Table 2, 3 and Appendix A). However, one anomaly was a significant increase in fine root biomass in the duff horizon of the light burn category of Douglas-fir following the burn (Table 2 and Appendix A). High variability among samples may be the underlying explanation of this result, but it is also possible that short-term recovery had already taken place (eg. the outliers were evidence of recolonization by spores) and an initial drop, if one occurred, was not detected by our sampling schedule.

All statistically significant changes in fine root biomass and mycorrhizal densities that appeared to be linked to fire effects were found in the shallow mineral soil. At 12 months post-fire, mean live fine root biomass in the shallow mineral soil in the light severity burn category was significantly reduced by an average of 45% for ponderosa pine and 78% for Douglas-fir. Root biomass in the moderate burn class in ponderosa pine were also lower post-fire, but not significantly ($p = 0.07$), likely a function of small sample size.

Declines of fine roots in fire-affected soils have been documented in other studies. Sweezy and Agee (1991) found that dry root weight was reduced by 50 and 70 percent at one and five months after burning in the top 10 cm of mineral soil and “forest floor” in burned units of ponderosa pine of central Oregon. In central Washington, Grier (1989) documented an immediate 60% reduction in fine roots under “heavy” burned plots of ponderosa pine in the top 5 cm of soil, but no change in “light” burned plots and an increase in control plots.

In the current study the density of mycorrhizae in shallow mineral soil of the light burn severity class declined in the post-fire samples by 79% for Douglas-fir and up to 94% for ponderosa pine. But, mycorrhizal densities also declined in shallow mineral soil in the control samples for both Douglas-fir (69%, $p = 0.05$) and ponderosa pine (59%, $p = 0.01$). Nonetheless, a comparison of post-fire groupings is appropriate since no pre-fire differences existed. For ponderosa pine, mycorrhizal density in shallow mineral soil was significantly lower in post-fire light burn than in post-fire control burn categories. For Douglas-fir, however, there was not a significant difference. Densities did not decrease significantly in the unburned plots within the treatment blocks. It is possible the unburned plots share a characteristic that both reduced their propensity to burn and affect seasonal mycorrhizal density patterns differently than the control (eg. moisture, temperature, aspect, canopy closure). Significant reductions in the control group suggest annual variations in mycorrhizal densities, irrespective of fire. An increase in mycorrhizal density in deep mineral soil of the unburned class of Douglas-fir plots, may also suggest that these unburned plots share a characteristic that sets their patterns of seasonal variation apart from other samples and reduced their propensity to burn.

Decreases in mycorrhizal density in fire-affected soils were also observed in other research (Wright and Tarrant 1958, Malajczuk and Hingston 1981, Schoenberger and Perry 1982, Parke et al. 1984). Herr et al. (1994) and Pilz and Perry (1984) observed no significant reductions in mycorrhizal density following fire. Using white pine seedlings planted without mycorrhizae, Herr et al. (1994) actually observed more mycorrhizal associations in those planted in burned units 2 months after a prescribed fire than those in unburned units.

In the current study, mycorrhizal density was expected to decrease with increased burn severity, but this effect was not observed (only ponderosa pine represented) (Figure 4). This contrasts findings of Wright and Tarrent (1958) who found a relationship between mycorrhizal reduction with increased burn severity. However, increases in mycorrhizal density associated with higher severities have also been observed (Herr et al. 1994). These discrepancies in the literature may have several explanations: 1) timing of the sampling since the disturbance; 2) season of the sampling and disturbance; 3) differing ages of the host and stand; 4) nutrient availability before and following disturbance; 5) use of different techniques for obtaining samples and quantifying mycorrhizae; 6) differing mycorrhizal and host species and seral stage of the stand; 7) the disturbance regime at that particular site; 8) different soil type and qualities; 9) different environmental characteristics affecting fire behavior.

A strong correlation was evident between fine root biomass reduction with both total organic consumption and residual organic depth for ponderosa pine. A regression model was fit to predict this loss (see equation 3) based on measurable indicators and may be useful in estimating fire effects. However, the reduction of fine roots and mycorrhizal densities for Douglas-fir and mycorrhizal density for ponderosa pine were not correlated with total organic consumption or residual organic depth (Appendix G). Even a thin layer of unburned organic material can insulate mineral soil from heat, drastically reducing peak temperatures. Frandsen and Ryan (1986) documented a drop of 320°C (from 680 to 360°C) when only 2 cm of dry moss (simulating duff) covered the soil. Valette et al. (1994) recorded an average 362°C temperature rise at the surface of bare mineral soil while duff covered surfaces increased only a 3 to 26°C, depending on the depth and moisture content of the duff. At least for ponderosa pine, wherever some duff remained, it's insulating properties likely provided sufficient protection to the roots and mycorrhizae below the surface.

Duff and litter moisture data were not available for our study site. Soil moisture was not closely correlated with fine root or mycorrhizal density decreases in the shallow mineral soil of the burned sample points. This was unexpected since increases in soil moisture have been directly linked to reductions in heat penetration. Frandsen and Ryan (1986) observed that when moisture was applied to mineral soil and simulated duff, the drop in temperature between the surface and duff/mineral soil interface was 600°C (from 680 to 80°C) and was greater than when the duff horizon was moisturized alone (from 680 to 430°C). The moisture in the mineral soil likely absorbed heat from the simulated duff leaving more unburned residue that both shielded the soil from peak temperatures and did not become a heat source by becoming available as fuel (Frandsen and Ryan 1986). However, the sensitivity of roots to heat from fire is thought to depend on season of burn, with the greatest sensitivity occurring in spring when soils are moist relative to other times of the year (Valette et al. 1994, Sweezy and Agee 1991). Several factors may be responsible; soil with high moisture content can be a better conductor of heat than dry soil, the roots have adjusted to cool soil over the winter months, roots may have begun actively growing and be most sensitive at this time, and/or trees in fire-prone areas of the Pacific Northwest are not adapted to early season fires (Grier 1989, Raison 1979, Frandsen and Ryan 1986, Valette et al. 1994). Soil moisture was only weakly correlated with total duff and litter consumption (Appendix G). No associations were found with pre-fire densities of mycorrhizae or roots (Appendix F). The lack of correlations between soil moisture and density reduction in our data likely reflects the complex and unpredictable nature of heat transfer under field conditions due to interactions of these factors along with variables associated with fire behavior, fuels characteristics, and soil qualities.

Despite an apparent relationship between the treatment and reduction of roots and mycorrhizae, the study was not designed to determine whether this was an immediate direct effect (i.e. tissue death from heat penetration into the soil) or a secondary (ie. response to lechate), or indirect effect (i.e. reduced carbon allocation to roots from nutrient flush in soil or damage to other parts of the host). Direct tissue death from heating may have been a factor if the fine roots and mycorrhizae were primarily located near the surface (ie. if most of the roots and mycorrhizae were in the top 2 cm of the shallow mineral soil horizon). However, the lack of correlation with organic consumption (pre-fire litter + pre-fire duff – post-fire litter - post-fire duff) or residue (post-fire litter depth + post-fire duff depth) in most cases may suggest a secondary or indirect factor is responsible for the decreasing levels of mycorrhizal density. Since the majority of burned plots were in the "light" category, it is unlikely that soil structure was significantly altered or that significant pyrolysis of nutrients occurred at sample points. In fact, a net increase in nutrient availability would be expected for these burn conditions, a possible alternative explanation for the drop in fine roots and mycorrhizae (DeLuca and Zouhar 2000, McNabb and Cromack 1990, Andersen and Rygiewicz 1991).

Although reductions in fine root biomass and mycorrhizal densities in response to fire have been documented, the threshold at which reductions affect tree health is not well understood.

No effect and negative effects on tree health have been observed following statistically significant reductions in mycorrhizae attributed to fire (Parke et al. 1984, Herr et al. 1994).

Summary and Conclusions

In this case study, it appears that a spring prescribed fire was associated with a decrease in fine root biomass in shallow mineral soil for both ponderosa pine and Douglas-fir and mycorrhizal density for ponderosa pine. Generally, litter and duff contained relatively small amounts of both mycorrhizae and fine roots, perhaps due to inhospitable moisture and temperature regimes, frequent disturbance, and/or constant sloughing of organic material on the steep slopes characteristic of this area. No statistically significant reductions were observed as a result of fire in these horizons, probably due to the small number of pre-fire samples that contained any fine roots or mycorrhizae. As expected, deep mineral soil did not appear to be effected by the treatment.

Although some significant differences did exist in mean fine root biomass and mycorrhizal densities between DBH classes, tree size was not a reliable or important factor. Sample position (distance from tree bole) also did not appear to be an important factor. Significant differences in fine root distribution was found between the species involved in this study.

Pre-fire (undisturbed) fine root biomass in shallow mineral soil did appear to be correlated with total organic depth above the soil on Douglas-fir plots. None of the other measured variables or calculated site conditions were significantly correlated with pre-fire fine root biomass and mycorrhizal densities for either Douglas-fir or ponderosa pine. Fine root and mycorrhizal reductions were not generally related to organic consumption or residual organic depth for Douglas-fir or mycorrhizal reduction for ponderosa pine. Only the reduction of fine root biomass of ponderosa pine was correlated with organic consumption and residual organic depth. A regression model was fit to predict fine root reduction in shallow mineral soil of ponderosa pine based on these variables. The model will be useful to estimate this effect of prescribed fire, although further study under different conditions is necessary. Research into the biological thresholds and repercussions of these reductions may also provide insight into the importance in short and long-term tree health and/or mortality rates.

From this and other research, it is apparent that fire effects on fine roots and mycorrhizal fungi are varied and complex and likely depend on the characteristics of the stand, available fuels and subsequent fire behavior and size, the soil properties which influence heat transfer, available nutrients, the original density and species composition of the fungi and their respective resistance to disturbance, the health of the host following the fire, the horizontal/spatial and vertical distribution of the fungi, and the ability to recolonize heavily disturbed sites. The study design, including sampling and laboratory timing and techniques, may also affect results. What remains to be determined is whether the reductions observed in our study area will constitute a deficiency and become a factor in the health of the host and subsequent mortality of the sample trees.

Currently, an anthropogenically altered fire regime is having an unknown effect on fine root and mycorrhizal diversity and distribution. Varying and sometimes conflicting results, from this and other research, ranging from an increase in fine roots and mycorrhizal fungi to soil sterilization emphasize the importance of one or more of the factors discussed in influencing these distributions and diversity, with potential ramifications for conserving biological and genetic below-ground diversity and forest health. Quantification of fire severity/intensity and effects should be standardized so more useful comparisons can be made between and within ecosystems. Furthermore, when interpreting results like these, we must appreciate that they are a culmination of a centuries-long disturbance regime. Similar research under a wide variety of field conditions would be beneficial to our understanding of these systems.

References

Agee, J.K. 1993. Fire Ecology of Pacific Northwest Forests. Island Press. Washington, D.C. 493 p.

Allen, M.F. 1991. The Ecology of Mycorrhizae. Cambridge University Press. Cambridge, England. 184 p.

Andersen, C.P. and P.T. Rygiewicz. 1991. Stress interactions and mycorrhizal plant response: understanding carbon allocation priorities. Env. Pollution. 73: 217-244.

Arno, S.F. 1987. Fire ecology and its management implications in ponderosa pine forests. P. 134-139 *in* Proc. of symp. on ponderosa pine: the species and its management.

Arno, S.F. 1997. Old growth ponderosa pine and western larch stand structures: Influences of pre-1900 fires and fire exclusion. USDA For. Serv. Res. Pap. INT-495.

Borchers, J.G. and D.A. Perry. 1990. Effects of Prescribed Fire on Soil Organisms. P. 143-157. *in* Natural and Prescribed Fire in Pacific Northwest Forests. Walstad, J.D., S.R. Radosevich and D.V. Sandberg (eds.). Oregon State University Press, Corvallis, OR.

Brady, N.C., and R.R. Weil. 1999. The Nature and Properties of Soil. Prentice-Hall. New Jersey. 621 p.

Brouwer, R., and C.T. DeWit. 1969. A simulation model of plant growth with special attention to root growth and its consequences. P. 224-244 *in* Root Growth. (Whittington, W.J. ed.). Butterworth, London.

Brown, J.K., M.R. Kaufmann, and W.D. Shepperd. 1999. Long term, landscape patterns of past fire events in a montane ponderosa pine forest of central Colorado. Landscape Ecol. 14: 513-532.

Brown, J.K., E.D. Reinhardt, and W.C. Fischer. 1991. Predicting duff and woody fuel consumption in Northern Idaho prescribed fires. For. Sci.. 37: 1550-1566.

Buchholz, K. and M. Gallagher. 1982. Initial ectomycorrhizal density response to wildfire in the New Jersey pine barren plains. Bul.Tor. Bot. Club. 109: 396-400.

Cairney, J.W.G., and S.M. Chambers. (eds.). 1999. Ectomycorrhizal Fungi: Key Genera in Profile. Sringer, New York. 369 p.

Davis, K.P. 1959. Forest Fire Control and Use. McGraw-Hill. New York. 686 p.

DeByle, N.V. 1981. Clearcutting and fire in the larch/ Douglas-fir forests of western Montana- a multifaceted research summary. UDSA For. Serv. Gen. Tech. Rep. INT-GTR-99.

DeLuca, T.H., and K.L. Zouhar. 2000. Effects of selection harvest and prescribed fire on soil nitrogen status of ponderosa pine forests. For. Ecol. and Mgt. 138: 263-271.

Dickinson, M.B., and E.A. Johnson. 2001. Fire effects on trees. P. 477-525. *In*: Forest Fires Behavior and Ecological Effects. Johnson, E.A., and K. Miyanishi (eds.) Academic Press, San Diego. 594 p.

Dix, N.J., and J. Webster. 1995. Fungal Ecology. Chapman and Hall. New York. 549 p.

Driscoll, K.G., J.M. Arocena, and H.B. Massicotte. 1999. Post-fire soil nitrogen content and vegetation composition in sub-boreal spruce forests of British Columbia's central interior, Canada. For. Ecol. Manage. 121: 227-237.

Flinn, M.A., and R.W. Wein. 1977. Depth of underground plant organs and theoretical survival during fire. Can. J. Bot. 55: 2550-2554.

Flint, H.R. 1925. Fire resistance of northern Rocky Mountain conifers. Idaho Forester 7(7):7-10, 41-43.

Frandsen, W.H. and K.C. Ryan.1986. Soil moisture reduces belowground heat flux and soil temperatures under a burning fuel pile. Can. J. For. Res. 16: 244-248.

Gessel, S.P., D.W. Cole, and E.C. Steinbrenner. 1973. Nitrogen balances in forest ecosystems of the Pacific Northwest. Soil Bio. and Biochem. 5:19-34.

Grier, C.C. 1989. Effects of prescribed springtime underburning on production and nutrient status of a young ponderosa pine stand. p 71-76 *in*: Multiresource Management of Ponderosa Pine Forests, USDA Forest Serv. Gen. Tech. Rep. RM-GTR-185.

Grime, J.P. 1977. Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. Am. Nat. 111:1169-1194.

Haase, S.M., and S.S. Sacket. 1998. Effects of prescribed fire in giant sequoia-mixed conifer stands in Sequoia and Kings Canyon National Parks. P. 236-243 *in:* Proc. of the 20th Tall Timbers Fire Ecology Conference. Tallahassee, Fl.

Hacskaylo, E. 1973. Carbohydrate physiology of ectomycorrhizae. P. 207-230 *in* Ectomycorrhizae: Their Ecology and Phsyiology. Marks, G.C., and T.T. Kozlowski (eds.). Academic Press, New York. 444 p.

Harley, J.L. 1989. The significance of mycorrhiza. Mycol. Res. 92(2): 129-139.

Harley, J.L., and S.E. Smith. 1983. Mycorrhizal Symbiosis. Academic Press, New York. 605 p.

Harvey, A.E., M.F. Jurgensen, and R.T. Graham. 1989. Fire-soil interactions governing site productivity in the northern Rocky Mountains P. 10-18 *in*: Symp. Proc. of the conference on Prescribed Fire in the Intermountain Region. Baumgartner, D.M., Neuenschwander, L.F., and Wakimoto, R.H. (eds.) Pullman, WA.

Harvey, A.E., M.F. Jurgensen, and M.J. Larsen. 1978. Seasonal distribution of ectomycorrhizae in a mature Douglas-fir/ larch forest soil in Western Montana. For. Sci. 24: 203-208.

Harvey, A.E., M.F. Jurgensen, and M.J. Larsen. 1980. Clearcut harvesting and ectomycorrhizae: survival of activity on residual roots and influence on a bordering forest stand in western Montana. Can. J. For. Res. 10: 300-303.

Harvey, A.E., M.J. Larsen, and M.F. Jurgensen. 1976. Distribution of ectomycorrhizae in a mature Douglas-fir/ Larch forest soil in Western Montana. For. Sci. 22: 393-398.

Harvey, A.E., M.J. Larsen, and M.F. Jurgensen. 1979. Comparitive distribution of ectomycorrhizae in soils of three Western Montana forest habitat types. For. Sci. 25: 350-358.

Herr, D.G., L.C. Duchesne, R. Tellier, R.S. McAlpine, and R.L. Peterson. 1994. Effect of prescribed burning on the ectomycorrhizal infectivity of a forest soil. Int. J. Wildland Fire. 4: 95-102.

Hitchcock, C.L., and A. Cronquist. 1973. Flora of the Pacific Northwest. University of Washington Press. Seattle. 730 p.

Ingram, D.L. and Buchanan, D. 1981. Measurement of direct heat injury of roots of three woody plants. Hort. science. 16: 769-771.

Last, F.T., J. Dighton, and P.A. Mason. 1987. Successions of sheathing mycorrhizal fungi. Trends in Ecol. and Evol. 2: 159-161.

Malajczuk, N. and F.J. Hingston. 1981. Ectomycorrhizae associated with Jarrah. Aust. J. Bot. 29: 453-462.

Marshal, J.D. and R.H. Waring. 1985. Predicting fine root production and turnover by monitoring root starch and soil temperature. Can. J. For. Res. 15: 791-800.

McNabb, D.H., and K.C. Cromack, Jr. 1990. Effects of prescribed fire on nutrients and soil productivity. P. 125-142 *in* Natural and Prescribed Fire in Pacific Northwest Forests. Walstad, J.D., S.R. Tadosevich, and D.V. Sandberg. Oregon State University Press, Corvallis, OR.

Neary, D.G., C.C. Klopatek, L.F. DeBano, and P.F. Ffolliott. 1999. Fire effects on belowground sustainability: a review and synthesis. For. Ecol. Manage. 122: 51-71.

Nylund, J.E. 1988. The regulation of mycorrhiza formation- carbohydrate and hormone theories reviewed. Scand. J. For. Res. 3: 465-479.

O'Laughlin, J., and P.S. Cook. 2003. Inventory-based forest health indicators. J. For. 101: 11-17.

Oliveira, M.R.G., M. van Noordwijk, S.R. Gaze, G. Brouwer, S. Bona, G. Mosca, and K. Hairiah. 2000. Auger sampling, ingrowth cores and pinboard methods. P. 175-210 *in* Root Methods: a Handbook. Smit, A.L., A.G. Bengough, C. Engels, M.van Noordwijk, S. Pellerin, S.C. van De Geijn (eds.). Springer. New York. 587 p.

Pankow, W., M. Niederer, U. Weiser, B. Schmid, T. Boller, and A.A. Weimken. 1989. Biochemical symptoms of stress in the mycorrhizal roots of Norway spruce (*Picea abies*). Trees. 3: 65-72.

Parke, J.L., R.G. Linderman, and J.M. Trappe. 1983. Effect of root zone temperature on ectomycorrhizal and vesicular-arbuscular mycorrhiza formation in disturbed and undisturbed forest soils of southwest Oregon. Can. J. For. Res. 13: 657-665.

Parke, J.L., R.G. Linderman, and J.M. Trappe. 1984. Inoculum potential of ectomycorrhizal fungi in forest soils of southwest Oregon and northern California. For. Sci. 30: 300-304.

Peterson, D.L. 1985. Crown scorch volume and scorch height: estimates of post-fire tree condition. Can. J. For. Res. 15: 596-598.

Peterson, D.L., and M.J. Arbaugh. 1986. Postfire survival in Douglas-fir and lodgepole pine: comparing the effects of crown and bole damage. Can. J. For. Res. 16: 1175-1179.

Pilz, D.P., and Perry, D.A. 1984. Impact of clear-cutting and slash burning on ectomycorrhizal associations of Douglas-fir. Can. J. For. Res. 14: 94-100.

Progar, R., K. Geier-Hayes, T Jackson, and T.L. Cook. 2002. Proposal to Joint Fire Science fund: Impacts of prescribed burning on the survival of Douglas-fir and ponderosa pine in the Boise National Forest. USDA For. Serv. Boise, Id. 16 p.

Raison, R.J., P.V. Woods, B.F. Jakobsen, and G.A.V. Bary. 1986. Soil temperatures during and following low-intensity prescribed burning in a *Eucalyptus pauciflora* forest. Aust. J. Soil. Res. 24: 33-47.

Read, D.J., R. Francis, and R.D. Finlay. 1985. Mycorrhizal mycelia and nutrient cycling in plant communities. P. 193-217 *in*: Ecological Interactions in Soil: Plants, Microbes and Animals. Fitter, A.H., D. Atkinson, D.J. Read, and M.B. Usher (eds.). Blackwell Scientific Publications, Oxford.

Reddell, P., and N. Malajczuk. 1984. Formation of mycorrhizae by jarrah (*Eucalyptus marginata* Donn ex Smith) in litter and soil. Aust. J. Bot. 32: 511-520.

Reeves, F.B., D. Wagner, T. Moorman, and J. Kiel. 1979. The role of endomycorrhizae in revegetation practices in the semi-arid west. I. a comparison of incidence of mycorrhizae in severely disturbed vs. natural environments. Amer. J. Bot. 66: 6-13.

Ritter, T., I. Kottke, F. Oberwinkler, and U. Tubingen. 1989. Vitality and ageing of the ectomycorrhizae of damaged and undamaged trees. Ag. Eco. and Env. 28: 415-419.

Robichaud, P.R. 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. J. Hydrol. 231-232: 220-229.

Ross, J.P. 1980. Effect of nontreated field soil on sporulation of vesicular-arbuscular mycorrhizal fungi associated with soybean. New Phytol. 70: 1200-1205.

Rovira, A.D., and G.D. Bowen. 1966. The effects of microorganisms upon plant growth. II. Detoxification of heat sterilized soils by fungi and bacteria. Plant and Soil. 25: 129-142.

Ruehle, J.L., D.H. Marx, J.P. Barnett, and W.H. Pawuk. 1981. Survival and growth of container grown and bare root shortleaf pine seedlings with *Pisolithus* and *Thelephora* ectomycorrhizae. South. J. For. Res. 12: 343-353.

Ryan, K.C. 1982. Fire- it's field effects: Techniques for assessing fire damage to trees. P. 1-11 *in* Proc. of Symp. of Intermountain Fire Council and Rocky Mountain Fire Council. Jackson, WY.

Ryan, K.C. 1982. Evaluating potential tree mortality from prescribed burning. P. 167-179 *in* Site preperation and fuels management on steep terrain. D.M. Baumgartner (ed.). Washington St. Univ. Coop. Ext.

Ryan, K.C., and W.H. Frandsen 1991. Basal injury from smoldering fires in mature *Pinus ponderosa* Laws. Int. J. Wildland Fire. 1: 107-118.

Ryan, K.C., and E.D. Reinhardt. 1988. Predicting postfire mortality of seven western conifers. Can. J. For. Res. 18: 1291-1297.

Ryan, K.C., D.L. Peterson, E.D. Reinhardt. 1988. Modeling long-term fire-caused mortality of Douglas-fir. For. Sci. 34: 190-199.

Saveland, J.M. and S.C. Bunting. 1987. Fire effects in ponderosa pine forests. P. 134-139 *in* Ponderosa Pine: The Species and its management, conference proceedings. Spokane, WA.

Schoenberger, M.M., D.A. Perry. 1982. The effect of soil disturbance on growth and ectomycorrhizae of Douglas-fir and western hemlock seedlings: a greenhouse bioassay. Can. J. For. Res. 12: 343-353.

Sloan, J.P. 1998. Historical density and stand structure of an old-growth forest in the Boise Basin of central Idaho. P. 258-266 *in* Proc. on 20th Symp. Tall Timbers Fire Ecology Conference, Fire in Ecosystem Management: Shifting the Paradigm from Suppression to Prescription. Pruden, T.L. and Brennan, L.A. (eds.). Tallahassee, FL.

Starker, T.J. 1934. Fire resistance in the forest. J. For. 32: 462-67.

Steele, R. S.F. Arno, K. Geier-Hayes. 1986. Wildfire patterns change in central Idaho's ponderosa pine-Douglas-fir forest. West. J. App. For. 1: 16-18.

Swezy, D.M. and J.K. Agee. 1990. Prescribed-fire effects on fine-root and tree mortality in old-growth ponderosa pine. Can. J. For. Res. 21: 626-634.

Tarrant, R.F. 1956. Changes in some physical soil properties after a prescribed burn in young ponderosa pine. J. For. 54: 439-441.

Thompson, B.D., A.D. Robson, and L.K. Abbott. 1990. Mycorrhizas formed by *Gigaspora calospora* and *Glomus fasciculatum* on subterranean clover in relation to soluble carbohydrate concentrations in roots. New Phytol. 114: 217-225.

Trofymow, J.A., and R. van den Driessche. 1991. Mycorrhizas. P. 183-227 *in* Mineral Nutrition of Conifer Seedlings. van den Driessche, R. (ed.). CRC Press, Boston.

Valette, J., V. Gomandy, J. Marechal, C. Houssard, and D. Gillon. 1994. Heat transfer in soil during very low-intensity experimental fires: the role of duff and soil moisture content. Int. J. Wildland Fire. 4: 225-237.

VanSickle, F.S. and R.D. Hickman. 1959. The effect of understory competition on the growth rate of ponderosa pine in North central Oregon. J. For. 57: 852-853.

Visser, S. 1995. Ectomycorrhizal fulgal succession in jack pine stands following wildfire. New Phytol. 129: 389-401.

Vogt, K.A., C.C. Grier, C.E Meier, and R.L. Edmonds. 1982. Mycorrhizal role in net primary production and nutrient cycling in *Abies amabilis* ecosystems in western Washington. Ecology 63: 370-380.

Vogt, K.A. and H. Persson. 1991. Measuring growth and developtment of roots. P. 477-501 *in* Techniques and Approaches in Forest Tree Ecophysiology. Lassoie, J.P. and T.M. Hinckley (eds.). CRC Press, Boston. 599 p.

Voorhees, W.B., M. Amemiya, R.R. Allmaras, and W.E. Larson, 1971. Some effects of aggregate structure heterogeneity on root growth. Soil Sci. Soc. Am. Proc. 35: 638-643.

Voorhees, W.B., D.A. Farrell, and W.E. Larson. 1975. Soil strength and aeration effects on root elongation. Soil Sci. Soc. Am. Proc. 39: 948-953.

Wilcox, H.E. 1991. Mycorrhizae. P. 731-765 *in* Plant roots: the hidden half. Waisel, Y., A. Eshel, and U. Kafkafi (eds.). Marcel Dekker Inc., New York. 1002 p.

Wong, T.L., R.W. Harris, and R.E. Fissel. 1971. Influence of high soil temperatures on five woody-plant species. J. Amer. Soc. Hort. Sci. 96: 80-83.

Wright, E. and R.F. Tarrant. 1958. Occurrence of mycorrhizae after logging and slash burning in the Douglas-fir forest type. USDA For. Serv. Res. Not. PNW-RN-160.

Wright, H.A. 1970. A method to determine heat-caused mortality in bunchgrass. Ecology 51: 582-587.

Wyant, J.G., R.D. Laven, and P.N. Omi. 1983. Fire effects on shoot growth characteristics of ponderosa pine in Colorado. Can. J. For. Res. 13: 620-625.

Wyant, J.G., P.N. Omi, R.D. Laven. 1986. Fire induced tree mortality in a Colorado ponderosa pine/ Douglas-fir stand. For. Sci. 32: 49-59.

Zak, B. 1971. Characterization and identification of Douglas-fir mycorrhizae. P. 38-53 *in* Mycorrhizae. Hacskaylo, E. (ed.). USDA For. Serv. Misc. Pub. 1189.

Appendix A. Descriptive statistics by severity and sample period for each species.

Table A. Mean fine root weight (g/l) by burn status and sample period for Douglas-fir sample plots.

Block/Severity	Horizon	Oct., 2001			Fire	May, 2002			July, 2002			Oct., 2002		
		mean[3] (SD)[4]	N[5] prop[6]	N[7] prop[8]		mean[3] (SD)[4]	N[5] prop[6]	N[7] prop[8]	mean[3] (SD)[4]	N[5] prop[6]	N[7] prop[8]	mean[3] (SD)[4]	N[5] prop[6]	N[7] prop[8]
Control	Litter	0.1[3] (0.33)[4]	20[5] (1.00)[6]	3[7] (0.15)[8]		0.00 (0.00)	2 (1.00)	0 (0.00)	0.12 (0.23)	4 (1.00)	1 (0.25)	0.09 (0.35)	20 (1.0)	3 (0.15)
	Duff	0.80 (1.10)	19 (0.95)	10 (0.63)		1.47 (2.08)	2 (1.00)	1 (0.50)	2.54 (2.20)	3 (0.75)	2 (0.66)	1.89 (4.82)	15 (0.75)	8 (0.53)
	SMS[1]	1.67 (0.93)	20 (1.00)	20 (1.00)		2.52 (0.09)	2 (1.00)	2 (1.00)	1.38 (0.48)	4 (1.00)	4 (1.00)	8.84 (24.06)	20 (1.00)	19 (0.95)
	DMS[2]	1.94 (1.02)	20 (1.00)	20 (1.00)		1.04 (na)	1 (0.50)	1 (1.00)	2.97 (1.20)	4 (1.00)	4 (1.00)	1.79 (1.99)	17 (0.85)	15 (0.88)
Burn blocks/ Unburned	Litter	0.13 (0.31)	40 (0.95)	8 (0.20)		0.00 (na)	1 (1.00)	0 (0.00)	na (na)	0 (0.00)	0 (0.00)	0.09 (0.53)	37 (0.88)	2 (0.05)
	Duff	1.09 (1.91)	30 (0.71)	22 (0.61)		10.35 (na)	1 (1.00)	1 (1.00)	1.40 (na)	1 (1.00)	1 (1.00)	0.63 (1.35)	27 (0.64)	12 (0.44)
	SMS	2.43 (1.72)	41 (0.98)	41 (1.00)		1.91 (na)	1 (1.00)	1 (1.00)	3.61 (na)	1 (1.00)	1 (1.00)	2.11 (2.15)	38 (0.90)	35 (0.92)
	DMS	2.21 (1.47)	34 (0.81)	34 (1.00)		1.00 (na)	1 (1.00)	1 (1.00)	2.50 (na)	1 (1.00)	1 (1.00)	2.96 (1.51)	31 (0.74)	30 (0.97)
Burn blocks/ Light	Litter	0.00 (0.01)	13 (0.93)	1 (0.08)		0.12 (0.23)	4 (08.0)	1 (0.25)	0.00 (na)	1 (0.20)	0 (0.00)	2.87 (6.90)	7 (0.50)	2 (0.29)
	Duff	2.30 (6.40)	14 (1.00)	6 (0.43)		1.21 (1.81)	4 (0.80)	4 (1.00)	0.32 (0.45)	2 (0.40)	1 (0.50)	0.34 (0.93)	9 (0.64)	3 (0.33)
	SMS	3.30 (2.24)	14 (1.00)	14 (1.00)		2.07 (1.13)	5 (1.00)	5 (1.00)	1.90 (0.86)	5 (1.00)	5 (1.00)	1.20 (1.20)	14 (1.00)	12 (0.86)
	DMS	2.92 (1.94)	14 (0.86)	12 (1.00)		2.85 (1.19)	5 (1.00)	5 (1.00)	2.00 (1.11)	4 (0.80)	4 (1.00)	3.08 (1.53)	10 (0.71)	10 (1.00)

[1] Shallow mineral soil

[2] Deep mineral soil

[3] Arithmetic mean

[4] Standard deviation

[5] Number of cores containing this horizon

[6] Proportion of cores containing this horizon

[7] Number of horizons containing any fine roots

[8] Proportion of horizons containing any fine roots

Appendix A (continued)

Table B. Mean fine root weight (g/l) by burn status and sample period for ponderosa pine sample plots.

Block/Severity	Horizon	Oct., 2001			Fire	May, 2002			July, 2002			Oct., 2002		
		mean[3]	N[5]	N[7]		mean[3]	N[5]	N[7]	mean[3]	N[5]	N[7]	mean[3]	N[5]	N[7]
		(SD)[4]	prop[6]	prop[8]		(SD)[4]	prop[6]	prop[8]	(SD)[4]	prop[6]	prop[8]	(SD)[4]	prop[6]	prop[8]
Control	Litter	0.00	20	0		0.00	2	0	0.18	4	1	0.31	19	4
		(0.00)	(1.00)	(0.00)		(0.00)	(1.00)	(0.00)	(0.37)	(1.00)	(0.25)	(0.79)	(0.95)	(0.21)
	Duff	1.51	20	10		0.00	2	0	0.00	1	0	3.10	18	6
		(3.15)	(0.50)	(0.50)		(0.00)	(1.00)	(0.00)	(na)	(0.25)	(0.00)	(7.11)	(0.90)	(0.33)
	SMS[1]	1.43	20	20		0.25	2	2	1.37	4	4	1.38	20	20
		(0.83)	(1.0)	(1.0)		(0.26)	(1.00)	(1.00)	(1.12)	(1.00)	(1.00)	(1.29)	(1.00)	(1.00)
	DMS[2]	1.77	20	20		0.90	2	2	1.57	4	4	3.68	16	16
		(1.01)	(1.0)	(1.0)		(1.16)	(1.00)	(1.00)	(0.90)	(1.00)	(1.00)	(8.03)	(0.80)	(1.00)
Burn blocks/ Unburned	Litter	0.25	34	9		0.00	2	0	0.00	1	0	1.38	27	4
		(0.76)	(1.00)	(0.26)		(0.00)	(1.00)	(0.00)	(na)	(1.00)	(0.00)	(6.48)	(0.79)	(0.15)
	Duff	1.56	26	17		0.56	2	2	0.00	1	0	1.85	12	6
		(2.49)	(0.76)	(0.65)		(0.63)	(1.00)	(1.00)	(na)	(1.00)	(0.00)	(4.98)	(0.35)	(0.50)
	SMS	1.91	33	32		0.68	2	2	na	0	0	2.54	33	28
		(1.69)	(0.97)	(0.97)		(0.04)	(1.00)	(1.00)	(na)	(0.00)	(0.00)	(8.25)	(0.97)	(0.85)
	DMS	2.28	26	26		2.33	2	1	na	0	0	1.73	26	26
		(1.31)	(0.76)	(1.00)		(na)	(0.50)	(1.00)	(na)	(0.00)	(0.00)	(1.00)	(0.76)	(1.00)
Burn blocks/ Light	Litter	0.33	17	16		0.07	2	1	0.00	2	0	0.00	17	7
		(1.16)	(0.94)	(0.25)		(0.09)	(0.67)	(0.50)	(0.00)	(1.00)	(0.00)	(0.00)	(0.41)	(0.00)
	Duff	0.72	14	10		4.33	2	2	0.00	1	0	0.00	3	0
		(0.75)	(0.82)	(0.71)		(6.04)	(0.67)	(1.00)	(na)	(0.50)	(0.00)	(0.00)	(0.18)	(0.00)
	SMS	1.86	17	16		1.12	3	3	0.38	2	2	1.03	17	14
		(1.33)	(1.00)	(0.94)		(1.09)	(1.00)	(1.00)	(0.08)	(1.00)	(1.00)	(1.67)	(1.00)	(0.82)
	DMS	2.02	12	12		0.99	2	2	5.19	1	1	2.09	11	10
		(1.79)	(0.71)	(1.00)		(0.39)	(0.67)	(1.00)	(na)	(0.50)	(1.00)	(1.72)	(0.65)	(0.91)

Appendix A (continued)

Burn blocks/ Moderate	Litter	0.38	7	1	0.00	0	0	0.00	0	0	0.00	0	0
		(1.00)	(1.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
	Duff	0.54	7	5	0.00	0	0	0.00	1	0	0.00	0	0
		(0.71)	(1.00)	(0.71)	(0.00)	(0.00)	(0.00)	(0.00)	(0.33)	(0.00)	(0.00)	(0.00)	(0.00)
	SMS	3.54	7	7	0.35	1	1	1.40	3	3	0.79	7	7
		(3.84)	(1.00)	(1.00)	(0.00)	(1.00)	(1.00)	(1.51)	(1.00)	(1.00)	(0.35)	(1.00)	(1.00)
	DMS	2.04	5	5	1.26	1	1	1.57	3	3	2.35	6	6
		(1.83)	(0.71)	(1.00)	(0.00)	(1.00)	(1.00)	(0.68)	(1.00)	(1.00)	(1.79)	(0.86)	(1.00)

[1] Shallow mineral soil
[2] Deep mineral soil
[3] Arithmetic mean
[4] Standard deviation
[5] Number of cores containing this horizon
[6] Proportion of cores containing this horizon
[7] Number of horizons containing any fine roots
[8] Proportion of horizons containing any fine roots

Appendix A (continued)

Table C. Mean mycorrhizal density (root tip/l) by burn status and sample period for Douglas-fir plots.

Block/Severity	Horizon	Oct., 2001			Fire	May, 2002			July, 2002			Oct., 2002		
		mean[3]	N[5]	N[7]		mean[3]	N[5]	N[7]	mean[3]	N[5]	N[7]	mean[3]	N[5]	N[7]
		(SD)[4]	prop[6]	prop[8]		(SD)[4]	prop[6]	prop[8]	(SD)[4]	prop[6]	prop[8]	(SD)[4]	prop[6]	prop[8]
Control	Litter	1.16	20	1		0.00	2	0	0.00	4	0	0.00	20	0
		(5.20)	(1.00)	(0.05)		(0.00)	(1.00)	(0.00)	(0.00)	(1.00)	(0.00)	(0.00)	(1.00)	(0.00)
	Duff	11.32	19	5		3.88	2	1	0.00	3	0	3.88	15	1
		(25.44)	(0.95)	(0.26)		(5.48)	(1.00)	(0.50)	(0.00)	(0.00)	(0.00)	(15.02)	(0.75)	(0.07)
	SMS[1]	113.06	20	17		98.48	2	2	84.33	4	4	35.13	20	17
		(118.15)	(1.00)	(0.85)		(112.95)	(1.00)	(1.00)	(65.37)	(1.00)	(1.00)	(45.70)	(1.00)	(0.85)
	DMS[2]	41.47	20	19		9.54	1	1	23.09	4	4	41.13	17	13
		(54.65)	(1.00)	(0.97)		(na)	(0.50)	(1.00)	(18.75)	(1.00)	(1.00)	(60.48)	(0.85)	(0.76)
Burn blocks/ Unburned	Litter	6.40	40	3		0.00	1	0	0.00	0	0	0.25	37	1
		(29.78)	(0.95)	(0.08)		(na)	(1.00)	(0.00)	(na)	(0.00)	(0.00)	(1.53)	(0.88)	(0.03)
	Duff	15.24	36	9		87.24	1	1	7.75	1	1	4.58	27	5
		(41.82)	(0.86)	(0.25)		(na)	(1.00)	(1.00)	(na)	(1.00)	(1.00)	(11.20)	(0.64)	(0.19)
	SMS	47.95	41	34		67.46	1	1	13.96	1	1	37.16	38	36
		(61.73)	(0.98)	(0.83)		(na)	(1.00)	(1.00)	(na)	(1.00)	(1.00)	(33.95)	(0.90)	(0.95)
	DMS	15.51	34	27		12.53	1	1	23.26	1	1	36.69	31	29
		(16.98)	(0.81)	(0.79)		(na)	(1.00)	(1.00)	(na)	(1.00)	(1.00)	(36.70)	(0.74)	(0.94)
Burn blocks/ Light	Litter	0.00	13	0		0.00	4	0	0.00	1	0	0.00	7	0
		(0.00)	(0.93)	(0.00)		(0.00)	(0.80)	(0.00)	(na)	(0.20)	(0.00)	(0.00)	(0.50)	(0.00)
	Duff	42.10	14	4		58.16	4	1	0.00	2	0	0.25	9	1
		(89.25)	(1.00)	(0.29)		(116.31)	(0.80)	(0.25)	(0.00)	(0.40)	(0.00)	(0.74)	(0.64)	(0.11)
	SMS	96.24	14	14		119.11	5	5	33.42	5	4	19.85	14	9
		(135.34)	(1.00)	(1.00)		(79.90)	(1.00)	(1.00)	(22.26)	(1.00)	(0.80)	(26.05)	(1.00)	(0.64)
	DMS	31.81	12	9		58.67	5	5	9.37	4	4	71.28	10	9
		(31.64)	(0.86)	(0.75)		(44.37)	(1.00)	(1.00)	(9.80)	(0.80)	(1.00)	(108.57)	(0.71)	(0.90)

[1] Shallow mineral soil

[2] Deep mineral soil

[3] Arithmetic mean

[4] Standard deviation

[5] Number of cores containing this horizon

[6] Proportion of cores containing this horizon

[7] Number of horizons containing any fine roots

[8] Proportion of horizons containing any fine roots

Appendix A (continued)

Table D. Mean mycorrhizal density (root tips/l) by burn status and sample period for ponderosa pine plots.

Block/Severity	Horizon	Oct., 2001			Fire	May, 2002			July, 2002			Oct., 2002		
		mean[3]	N[5]	N[7]		mean[3]	N[5]	N[7]	mean[3]	N[5]	N[7]	mean[3]	N[5]	N[7]
		(SD)[4]	prop[6]	prop[8]		(SD)[4]	prop[6]	prop[8]	(SD)[4]	prop[6]	prop[8]	(SD)[4]	prop[6]	prop[8]
Control	Litter	0.00	20	0		0.00	2	0	0.00	4	0	13.06	19	1
		(0.00)	(1.00)	(0.00)		(0.00)	(1.00)	(0.00)	(0.00)	(1.00)	(0.00)	(56.93)	(0.95)	(0.05)
	Duff	2.32	20	1		0.00	2	0	0.00	1	0	183.52	18	1
		(10.40)	(1.00)	(0.05)		(0.00)	(1.00)	(0.00)	(na)	(0.25)	(0.00)	(635.73)	(0.90)	(0.06)
	SMS[1]	123.53	20	20		18.90	2	1	34.31	4	2	50.20	20	14
		(154.03)	(1.00)	(1.00)		(26.73)	(1.00)	(0.50)	(65.56)	(1.00)	(0.50)	(70.41)	(1.00)	(0.70)
	DMS[2]	42.55	20	19		39.37	2	2	47.91	4	3	68.06	16	16
		(50.89)_	(1.00)	(0.95)		(10.12)	(1.00)	(1.00)	(56.69)	(1.00)	(0.75)	(66.95)	(0.80)	(1.00)
Burn blocks/ Unburned	Litter	4.10	34	1		0.00	2	0	0.00	1	0	0.86	27	1
		(23.94)	(1.00)	(0.03)		(0.00)	(1.00)	(0.00)	(na)	(1.00)	(0.00)	(4.48)	(0.79)	(0.04)
	Duff	19.37	26	7		45.56	2	2	0.00	1	0	2.91	12	1
		(68.16)	(0.76)	(0.27)		(56.20)	(1.00)	(1.00)	(na)	(1.00)	(0.00)	(10.07)	(0.35)	(0.08)
	SMS	51.95	33	27		6.44	2	2	0.00	0	0	65.68	33	24
		(60.70)	(0.97)	(0.82)		(4.05)	(1.00)	(1.00)	(na)	(0.00)	(0.00)	(135.65)	(0.97)	(0.73)
	DMS	54.95	26	22		19.94	1	1	0.00	0	0	68.92	26	25
		(78.49)	(0.76)	(0.85)		(na)	(0.50)	(1.00)	(na)	(0.00)	(0.00)	(88.14)	(0.76)	(0.96)
Burn blocks/ Light	Litter	0.79	16	1		0.00	2	0	0.00	2	0	0.00	7	0
		(3.17)	(0.94)	(0.06)		(0.00)	(0.67)	(0.00)	(0.00)	(1.00)	(0.00)	(0.00)	(0.41)	(0.00)
	Duff	8.32	14	4		0.00	2	0	0.00	1	0	0.00	3	0
		(16.90)	(0.82)	(0.29)		(0.00)	(0.67)	(0.00)	(na)	(0.50)	(0.00)	(0.00)	(0.18)	(0.00)
	SMS	73.47	17	14		27.92	3	2	15.12	2	1	4.52	17	7
		(109.59)	(1.00)	(0.82)		(33.55)	(1.00)	(0.67)	(21.38)	(1.00)	(0.50)	(7.42)	(1.00)	(0.41)
	DMS	36.23	12	9		19.63	2	2	10.86	1	1	27.44	11	10
		(42.73)	(0.71)	(0.75)		(2.60)	(0.67)	(1.00)	(na)	(0.50)	(1.00)	(41.24)	(0.65)	(0.91)

Appendix A (continued)

Burn blocks/	Litter	0.00	7	0	0.00	0	0	0.00	0	0	0.00	0	0
Moderate		(0.00)	(1.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
	Duff	10.71	7	3	0.00	0	0	0.00	1	0	0.00	0	0
		(15.10)	(1.00)	(0.43)	(0.00)	(0.00)	(0.00)	(na)	(0.33)	(0.00)	(0.00)	(0.00)	(0.00)
	SMS	37.89	7	7	0.00	1	0	9.31	3	2	12.30	7	5
		(30.50)	(1.00)	(1.00)	(na)	(1.00)	(0.00)	(14.15)	(1.00)	(0.67)	(12.43)	(1.00)	(0.71)
	DMS	69.72	5	4	87.58	1	1	14.42	3	3	25.13	6	4
		(78.73)	(0.71)	(0.80)	(na)	(1.00)	(1.00)	(11.03)	(1.00)	1.00)	(36.62)	(0.86)	(0.67)

[1] Shallow mineral soil
[2] Deep mineral soil
[3] Arithmetic mean
[4] Standard deviation
[5] Number of cores containing this horizon
[6] Proportion of cores containing this horizon
[7] Number of horizons containing any fine roots
[8] Proportion of horizons containing any fine roots

Appendix B. Pre-fire fine root biomass and mycorrhizal density tests by horizon for each species.

Table A. Pre-fire root biomass (g/l) between horizons of Douglas-fir.

ANOVA model results.

Source	DF	SS	F	P
Horizon	4	10.04	59.54	<.001
Error	279	11.76		
total	283	21.8		

Fishers LSD multiple comparisons.

	1	2	3	4
1 Litter	1.00			
2 Duff	<0.01	1.00		
3 SMS	<0.01	<0.01	1.00	
4 DMS	<0.01	<0.01	0.91	1.00

Adjusted means ranked from smallest to largest values.

Rank	Horizon	Means
1	Litter	0.10
2	Duff	1.26
3	SMS	2.39
4	DMS	2.26

Table B. Pre-fire mycorrhizal root tips/l between horizons for Douglas-fir.

ANOVA model results.

Source	DF	SS	F	P
Horizon	4	83.72	49.75	<.001
Error	279	117.37		
total	283			

Fishers LSD multiple comparisons.

	1	2	3	4
1 Litter	1.00			
2 Duff	<0.01	1.00		
3 SMS	<0.01	<0.01	1.00	
4 DMS	<0.01	<0.01	<0.01	1.00

Adjusted means ranked from smallest to larges values.

Rank	Horizon	Means
1	Litter	3.82
2	Duff	19.61
3	SMS	74.33
4	DMS	26.34

Appendix B (continued)

Table C. Pre-fire root biomass (g/l) between horizons of ponderosa pine.

ANOVA model results.

Source	DF	SS	F	P
Horizon	4	7.28	42.3	<.001
Error	280	12.05		
total	284	19.33		

Fishers LSD multiple comparisons.

	1	2	3	4
1 Litter	1.00			
2 Duff	<0.01	1.00		
3 SMS	<0.01	<0.01	1.00	
4 DMS	<0.01	<0.01	0.19	1.00

Adjusted means ranked from smallest to larges values.

Rank	Horizon	Means
1	Litter	0.22
2	Duff	1.26
3	SMS	1.79
4	DMS	2.05

Table D. Pre-fire mycorrhizal root tips/l between horizons for ponderosa pine.

ANOVA model results.

Source	DF	SS	F	P
Horizon	4	107.79	71.71	<.0001
Error	280	105.22		
total	284	213.01		

Fishers LSD multiple comparisons.

	1	2	3	4
1 Litter	1.00			
2 Duff	0.01	1.00		
3 SMS	<0.01	<0.01	1.00	
4 DMS	<0.01	<0.01	0.04	1.00

Adjusted means ranked from smallest to larges values.

Rank	Horizon	Means
1	Litter	1.98
2	Duff	11.07
3	SMS	74.01
4	DMS	48.62

Appendix C. Factorial ANOVA's and Fisher's LSD. Pre-fire fine root biomass and mycorrhizal density tests by DBH and sample position for each species.

Table A. Pre-fire fine root biomass (g/l) means by sample position and DBH size class for Douglas-fir litter.

ANOVA model results

Source	DF	SS	F	P
Model	19.00	0.15	1.02	0.46
Error	53.00	0.40		
Total	72.00	0.55		

Source	DF	SS	F	P
DBH	9.00	0.04	0.66	0.74
Position	1.00	<0.01	0.05	0.83
Interaction	9.00	0.10	1.49	0.18

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	17.78	0.00
2	27.94	0.00
3	58.42	0.00
4	22.86	0.04
5	48.26	0.08
6	33.02	0.13
7	43.18	0.16
8	38.10	0.16
9	63.50	0.20
10	53.34	0.23

Table B. Pre-fire fine root biomass (g/l) means by sample position and DBH size class for Douglas-fir duff.

ANOVA model results

Source	DF	SS	F	P
Model	19	1.55	1.08	0.39
Error	49	3.7		
Total	68	5.26		

Source	DF	SS	F	P
DBH	9	0.46	0.68	0.72
Position	1	0.01	0.10	0.75
Interaction	9	1.08	1.58	0.15

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	63.50	0.32
2	38.10	0.43
3	43.18	0.55
4	58.42	0.63
5	22.86	0.77
6	53.34	1.05
7	33.02	1.17
8	48.26	1.18
9	27.94	2.25
10	17.78	3.44

Appendix C (continued)

Table C. Pre-fire fine root biomass (g/l) means by sample position and DBH size class for Douglas-fir shallow mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	19	0.67	0.66	0.84
Error	55	2.94		
Total	74	3.61		

Source	DF	SS	F	P
DBH	9	0.27	0.57	0.81
Position	1	0.02	0.47	0.49
Interaction	9	0.38	0.79	0.63

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	17.78	2.00
2	63.50	2.01
3	33.02	2.07
4	58.42	2.17
5	43.18	2.27
6	48.26	2.38
7	22.86	2.45
8	27.94	2.57
9	53.34	2.99
10	38.10	3.18

Table D. Pre-fire fine root biomass (g/l) means by sample position and DBH size class for Douglas-fir deep mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	19	0.62	0.88	0.61
Error	46	1.73		
Total	65	2.35		

Source	DF	SS	F	P
DBH	9	0.29	0.85	0.58
Position	1	<0.01	0.03	0.87
Interaction	9	0.34	1.00	0.46

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	17.00	1.12
2	23.00	1.85
3	25.00	1.99
4	9.00	2.22
5	19.00	2.30
6	11.00	2.31
7	13.00	2.48
8	7.00	2.67
9	15.00	2.75
10	21.00	2.91

Appendix C (continued)

Table E. Pre-fire fine root biomass (g/l) means by sample position and DBH size class for ponderosa pine litter.

ANOVA model results

Source	DF	SS	F	P
Model	19	0.48	1.3	0.22
Error	57	1.12		
Total	76	1.61		

Source	DF	SS	F	P
DBH	9	0.41	2.33	0.03
Position	1	0.01	0.30	0.59
Interaction	9	0.07	0.38	0.94

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean	
1	22.86	0.00	a
2	33.02	0.00	ab
3	43.18	0.00	ab
4	53.34	0.06	ab
5	48.26	0.07	ab
6	17.78	0.09	ab
7	63.50	0.10	ab
8	27.94	0.12	ab
9	38.10	0.33	ab
10	58.42	1.33	b

Fishers LSD multiple comparisons

size	17.78	22.86	27.94	33.02	38.10	43.18	48.26	53.34	58.42	63.50
17.78	1.00									
22.86	0.66	1.00								
27.94	0.95	0.61	1.00							
33.02	0.66	1.00	0.61	1.00						
38.10	0.58	0.32	0.62	0.32	1.00					
43.18	0.67	1.00	0.62	1.00	0.32	1.00				
48.26	0.93	0.72	0.88	0.72	0.52	0.73	1.00			
53.34	0.89	0.80	0.85	0.80	0.54	0.81	0.96	1.00		
58.42	**0.00**	**0.00**	**0.00**	**0.00**	**0.01**	**0.00**	**0.00**	**0.01**	1.00	
63.50	1.00	0.66	0.95	0.66	0.58	0.67	0.93	0.90	0.00	1.00

Table F. Pre-fire fine root biomass (g/l) means by sample position and DBH size class for ponderosa-pine duff.

ANOVA model results

Source	DF	SS	F	P
Model	19	1.64	1	0.48
Error	47	4.06		
Total	66	5.7		

Source	DF	SS	F	P
DBH	9	1.02	1.31	0.25
Position	1	0.16	1.89	0.18
Interaction	9	0.37	0.47	0.89

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	27.94	0.07
2	63.50	0.17
3	38.10	0.42
4	53.34	0.73
5	22.86	1.24
6	33.02	1.31
7	17.78	1.40
8	48.26	1.70
9	58.42	2.68
10	43.18	2.74

Appendix C (continued)

Table G. Pre-fire fine root biomass (g/l) means by sample position and DBH size class for ponderosa pine shallow mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	19	1.09	1.88	0.03
Error	57	1.75		
Total	76	2.83		

Source	DF	SS	F	P
DBH	9	0.82	2.99	0.01
Position	1	0.02	0.71	0.40
Interaction	9	0.25	0.92	0.52

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Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	63.50	0.68
2	43.18	1.10
3	53.34	1.15
4	33.02	1.33
5	27.94	1.63
6	38.10	1.92
7	48.26	1.94
8	17.78	2.37
9	22.86	2.37

Fishers LSD multiple comparisons

size clas	17.78	22.86	27.94	33.02	38.10	43.18	48.26	53.34	58.42	63.50
17.78	1.00									
22.86	0.99	1.00								
27.94	0.12	0.13	1.00							
33.02	0.12	0.12	0.93	1.00						
38.1	0.35	0.35	0.54	0.50	1.00					
43.18	**0.02**	**0.02**	0.42	0.49	0.12	1.00				
48.26	0.43	0.44	0.45	0.41	0.88	0.12	1.00			
53.34	**0.04**	**0.04**	0.54	0.61	0.24	0.89	0.19	1.00		
58.42	0.45	0.44	**0.02**	**0.02**	0.09	**0.00**	0.12	**0.01**	1.00	
63.5	**0.00**	**0.00**	0.10	0.14	**0.03**	0.41	**0.02**	0.36	**0.00**	1.00

Table H. Pre-fire fine root biomass (g/l) means by sample position and DBH size class for ponderosa pine deep mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	19	0.56	0.95	0.53
Error	43	1.34		
Total	62	1.9		

Source	DF	SS	F	P
DBH	9	0.39	1.38	0.23
Position	1	<0.01	0.00	0.99
Interaction	9	0.16	0.56	0.82

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	33.02	1.13
2	63.50	1.47
3	48.26	1.59
4	27.94	1.82
5	53.34	1.91
6	43.18	1.98
7	38.10	2.14
8	17.78	2.25
9	58.42	2.31
10	22.86	4.06

Appendix C (continued)

Table I. Pre-fire mycorrhizal root tips/l means by sample position and DBH size class for Douglas-fir litter.

ANOVA model results

Source	DF	SS	F	P
Model	19	2.44	0.81	0.69
Error	53	8.41		
Total	72	10.85		

Source	DF	SS	F	P
DBH	9	1.50	1.05	0.42
Position	1	0.02	0.11	0.74
Interaction	9	0.93	0.65	0.75

Adjusted means ranked from smallest to larges values.

Rank	DBH	Mean
1	17.78	0.00
2	22.86	0.00
3	27.94	0.00
4	33.02	0.00
5	48.26	0.00
6	58.42	0.00
7	63.50	0.00
8	53.34	3.88
9	43.18	8.72
10	38.10	23.26

Table J. Pre-fire mycorrhizal root tips/l means by sample position and DBH size class for Douglas-fir duff.

ANOVA model results

Source	DF	SS	F	P
Model	19	12.73	1.17	0.32
Error	49	28.13		
Total	68	40.86		

Source	DF	SS	F	P
DBH	9	4.99	0.97	0.48
Position	1	0.49	0.87	0.36
Interaction	9	6.65	1.29	0.27

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	58.42	0.00
2	63.50	0.00
3	48.26	6.83
4	38.10	10.30
5	33.02	11.63
6	43.18	13.61
7	53.34	14.73
8	22.86	27.14
9	27.94	36.89
10	17.78	70.36

Appendix C (continued)

Table K. Pre-fire mycorrhizal root tips/l means by sample position and DBH size class for Douglas-fir shallow mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	19	13.87	1.51	0.12
Error	55	26.51		
Total	74	40.38		

Source	DF	SS	F	P
DBH	9	8.59	1.98	0.06
Position	1	0.01	0.02	0.88
Interaction	9	5.19	1.20	0.32

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	63.50	13.58
2	48.26	38.67
3	53.34	43.11
4	38.10	64.26
5	27.94	72.70
6	43.18	74.44
7	58.42	87.82
8	33.02	91.44
9	17.78	116.90
10	22.86	167.49

Table L. Pre-fire mycorrhizal root tips/l means by sample position and DBH size class for Douglas-fir deep mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	19	5.32	0.65	0.85
Error	46	19.52		
Total	65	25.28		

Source	DF	SS	F	P
DBH	9	2.72	0.70	0.71
Position	1	0.15	0.35	0.56
Interaction	9	2.40	0.62	0.78

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	38.10	10.87
2	53.34	13.44
3	27.94	15.80
4	48.26	21.01
5	43.18	23.98
6	58.42	25.44
7	63.50	27.23
8	17.78	28.73
9	33.02	45.76
10	22.86	67.15

Appendix C (continued)

Table M. Pre-fire mycorrhizal root tips/l means by sample period and DBH size class for ponderosa pine litter.

ANOVA model results

Source	DF	SS	F	P
Model	19	1.34	0.91	0.58
Error	57	4.43		
Total	76	5.76		

Source	DF	SS	F	P
DBH	9	1.21	1.73	0.10
Position	1	0.01	0.15	0.70
Interaction	9	0.11	0.16	1.00

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	17.78	0.00
2	22.86	0.00
3	27.94	0.00
4	33.02	0.00
5	38.10	0.00
6	43.18	0.00
7	48.26	0.00
8	53.34	0.00
9	63.50	0.00
10	58.42	19.03

Table N. Pre-fire mycorrhizal root tips/l means by sample period and DBH size class for ponderosa pine litter.

ANOVA model results

Source	DF	SS	F	P
Model	19	6.39	0.76	0.74
Error	47	20.79		
Total	66	27.18		

Source	DF	SS	F	P
DBH	9	3.78	0.95	0.49
Position	1	1.20	2.70	0.11
Interaction	9	1.31	0.33	0.96

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	22.86	0.00
2	27.94	0.00
3	63.50	1.33
4	17.78	4.15
5	38.10	7.44
6	48.26	7.53
7	43.18	7.95
8	33.02	8.40
9	53.34	11.45
10	58.42	69.79

Appendix C (continued)

Table O. Pre-fire mycorrhizal root tips/l means by sample
period and DBH size class for ponderosa pine shallow mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	19	6.99	0.65	0.85
Error	57	32.08		
Total	76	39.06		

Source	DF	SS	F	P
DBH	9	3.90	0.77	0.64
Position	1	0.06	0.11	0.74
Interaction	9	2.97	0.59	0.80

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	43.18	20.06
2	33.02	48.84
3	38.10	55.18
4	22.86	57.03
5	63.50	63.97
6	17.78	75.02
7	53.34	94.22
8	48.26	95.09
9	27.94	98.00
10	58.42	134.63

Table P. Pre-fire mycorrhizal root tips/l means by sample.
period and DBH size class for ponderosa pine deep mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	19	14.35	1.72	0.07
Error	43	18.87		
Total	62	33.22		

Source	DF	SS	F	P
DBH	9	8.61	2.18	0.04
Position	1	1.09	2.49	0.12
Interaction	9	5.02	1.27	0.28

Adjusted means ranked from smallest to larges values.

Rank	DBH	mean
1	33.02	7.05
2	17.78	26.15
3	48.26	29.45
4	43.18	32.52
5	58.42	35.08
6	63.50	47.44
7	22.86	60.60
8	38.10	73.95
9	53.34	86.61
10	27.94	88.63

Fishers LSD multiple comparisons

size class	17.78	22.86	27.94	33.02	38.10	43.18	48.26	53.34	58.42	63.50
17.78	1.00									
22.86	0.26	1.00								
27.94	0.14	0.88	1.00							
33.02	0.17	0.03	0.01	1.00						
38.10	0.04	0.41	0.43	0.00	1.00					
43.18	0.35	0.07	0.03	0.66	0.01	1.00				
48.26	0.73	0.40	0.26	0.10	0.08	0.22	1.00			
53.34	0.13	0.73	0.81	0.01	0.63	0.03	0.22	1.00		
58.42	0.98	0.25	0.14	0.18	0.04	0.36	0.72	0.13	1.00	
63.50	0.14	0.83	0.93	0.01	0.49	0.03	0.24	0.87	0.13	1.00

Appendix D ANOVA's and Fisher's LSD. Pre-fire fine root biomass and mycorrhizal density tests by post-fire severity classes and species.

Table A. Pre-fire fine root biomass by post-fire severity class and species in litter.

ANOVA model results

Source	DF	SS	F	P
Model	6	0.09	1.04	0.40
Error	143	2.07		
Total	149	2.16		

Source	DF	SS	F	P
Severity	3	0.04	1.01	0.39
Species	1	0.01	0.61	0.44
Interaction	2	0.04	1.29	0.28

Adjusted means ranked from smallest to largest

rank	species	severity	mean
1	PP	control	0.00
2	DF	light	0.00
3	DF	control	0.10
4	DF	unburn	0.13
5	PP	unburn	0.26
6	PP	light	0.33
7	PP	moderate	0.38

Table B. Pre-fire fine root biomass by post-fire severity class and species in duff.

ANOVA model results

Source	DF	SS	F	P
Model	6	0.10	0.21	0.97
Error	129	10.86		
Total	135	10.97		

Source	DF	SS	F	P
Severity	3	0.08	0.30	0.82
Species	1	<0.01	0.02	0.90
Interaction	2	0.03	0.17	0.85

Adjusted means ranked from smallest to largest

rank	species	severity	mean
1	PP	moderate	0.54
2	PP	light	0.72
3	DF	control	0.80
4	DF	unburn	1.09
5	PP	control	1.51
6	PP	unburn	1.56
7	DF	light	2.30

Appendix D (continued)

Table C. Pre-fire fine root biomass by post-fire severity class and species in shallow mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	6	0.51	2.00	0.07
Error	145	6.15		
Total	151	6.67		

Source	DF	SS	F	P
Severity	3	0.24	1.90	0.13
Species	1	0.25	5.87	0.02
Interaction	2	0.07	0.80	0.45

Adjusted means ranked from smallest to larg

rank	species	severity	mean
1	PP	control	1.43
2	DF	control	1.67
3	PP	light	1.86
4	PP	unburn	1.91
5	PP	moderate	2.09
6	DF	unburn	2.43
7	DF	light	3.30

Table D. Pre-fire fine root biomass by post-fire severity class and species in deep mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	6	0.17	0.84	0.54
Error	122	4.10		
Total	128	4.27		

Source	DF	SS	F	P
Severity	3	0.06	0.61	0.61
Species	1	0.05	1.39	0.24
Interaction	2	0.09	1.36	0.26

Adjusted means ranked from smallest to larg

rank	species	severity	mean
1	PP	control	1.77
2	DF	control	1.94
3	PP	light	2.02
4	PP	moderate	2.04
5	DF	unburn	2.21
6	PP	unburn	2.28
7	DF	light	2.92

Appendix D (continued)

Table E. Pre-fire mycorrhizal density by post-fire severity class and species in litter.

ANOVA model results

Source	DF	SS	F	P
Model	6	0.33	0.48	0.82
Error	143	16.37		
Total	149	16.70		

Source	DF	SS	F	P
Severity	3	0.15	0.43	0.73
Species	1	0.01	0.12	0.73
Interaction	2	0.11	0.47	0.62

Adjusted means ranked from smallest to larges

rank	species	severity	mean
1	DF	light	0.00
2	PP	control	0.00
3	PP	moderate	0.00
4	PP	light	0.79
5	DF	control	1.16
6	PP	unburn	4.11
7	DF	unburn	6.40

Table F. Pre-fire mycorrhizal density by post-fire severity class and species in duff.

ANOVA model results

Source	DF	SS	F	P
Model	6	2.68	0.88	0.51
Error	129	65.76		
Total	135	68.44		

Source	DF	SS	F	P
Severity	3	1.71	1.12	0.34
Species	1	0.77	1.50	0.22
Interaction	2	0.61	0.60	0.55

Adjusted means ranked from smallest to larges

rank	species	severity	mean
1	PP	moderate	0.54
2	PP	light	0.72
3	DF	control	0.80
4	DF	unburn	1.09
5	PP	control	1.51
6	PP	unburn	1.56
7	DF	light	2.30

Appendix D (continued)

Table G. Pre-fire mycorrhizal density by post-fire severity class and species in shallow mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	6	4.71	1.52	0.17
Error	145	74.76		
Total	151	79.47		

Source	DF	SS	F	P
Severity	3	4.06	2.63	0.05
Species	1	0.01	0.03	0.87
Interaction	2	0.61	0.59	0.56

Adjusted means ranked from smallest to larges

rank	species	severity	mean
1	PP	control	1.43
2	DF	control	1.67
3	PP	light	1.86
4	PP	unburn	1.91
5	PP	moderate	2.09
6	DF	unburn	2.43
7	DF	light	3.30

Fishers LSD multiple comparisons

	1	2	3	4
1 Control	1.00			
2 Light	0.24	1.00		
3 Moderate	0.44	0.94	1.00	
4 Unburn	0.01	0.21	0.55	1.00

Ranked significant comparisons

rank	species	mean
1	Control	1.71
2	Light	1.50
3	Moderate	1.48
4	Unburn	1.31

Table H. Pre-fire mycorrhizal density by post-fire severity class and species in deep mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	6	3.25	1.18	0.32
Error	122	56.10		
Total	128	59.35		

Source	DF	SS	F	P
Severity	3	1.21	0.88	0.45
Species	1	0.25	0.55	0.46
Interaction	2	1.08	1.17	0.31

Adjusted means ranked from smallest to larges

rank	species	severity	mean
1	PP	control	1.77
2	DF	control	1.94
3	PP	light	2.02
4	PP	moderate	2.04
5	DF	unburn	2.21
6	PP	unburn	2.28
7	DF	light	2.92

Appendix E ANOVA's and Fisher's LSD. Comparisons of mean fine root biomass and mycorrhizal densities by sample period and severity class for each species.

Table A. Fine root biomass (g/l) by sample period and severity class for Douglas-fir litter.

ANOVA model results

Source	DF	SS	F	P
Model	5	0.33	3.51	<.01
Error	131	2.50		
Total	136			

Source	DF	SS	F	P
Severity	2	0.14	3.60	0.03
Sample Period	1	0.12	6.41	0.01
Interaction	2	0.27	7.06	<.01

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	light	pre-fire	0.00
2	unburn	post-fire	0.09
3	control	post-fire	0.09
4	control	pre-fire	0.10
5	unburn	pre-fire	0.13
6	light	post-fire	2.87

Fishers LSD multiple comparisons

	1	2	3	4	5	6
1 Control pre-fire	1.00					
2 Control post-fire	0.90	1.00				
3 Light pre-fire	0.54	0.62	1.00			
4 Light post-fire	<0.01	<0.01	<0.01	1.00		
5 Unburn pre-fire	0.78	0.67	0.36	<0.01	1.00	
6 Unburn post-fire	0.73	0.84	0.71	<0.01	0.45	1.00

Table B. Fine root biomass (g/l) by sample period and severity class for Douglas-fir duff.

ANOVA model results

Source	DF	SS	F	P
Model	5	0.30	0.79	0.56
Error	114	0.77		
Total	119	9.07		

Source	DF	SS	F	P
Severity	2	0.05	0.32	0.73
Sample Period	1	0.13	1.68	0.20
Interaction	2	0.14	0.90	0.41

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	light	3	0.35
2	unburn	3	0.63
3	control	0	0.80
4	unburn	0	1.09
5	control	3	1.89
6	light	0	2.30

Appendix E (continued)

Table C. Fine root biomass (g/l) by sample period and severity class for Douglas-fir shallow mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	5	0.95	2.39	0.04
Error	141	11.23		
Total	146	12.19		

Source	DF	SS	F	P
Severity	2	0.05	0.29	0.75
Sample Period	1	0.13	1.59	0.21
Interaction	2	0.82	5.12	0.01

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	light	3	1.20
2	control	0	1.67
3	unburn	3	2.11
4	unburn	0	2.43
5	light	0	3.30
6	control	3	8.84

Fishers LSD multiple comparisons

	1	2	3	4	5	6
1 Control pre-fire	1.00					
2 Control post-fire	0.07	1.00				
3 Light pre-fire	0.08	0.92	1.00			
4 Light post-fire	0.28	0.01	0.01	1.00		
5 Unburn pre-fire	0.28	0.32	0.32	0.03	1.00	
6 Unburn post-fire	0.92	0.05	0.07	0.19	0.24	1.00

Table D. Fine root biomass (g/l) by sample period and severity class for Douglas-fir deep mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	5	0.57	3.10	0.01
Error	118	4.31		
Total	123	4.89		

Source	DF	SS	F	P
Severity	2	0.37	5.04	0.01
Sample Period	1	0.01	0.44	0.51
Interaction	2	0.17	2.31	0.10

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	control	3	1.79
2	control	0	1.94
3	unburn	0	2.21
4	light	0	2.92
5	unburn	3	2.96
6	light	3	3.08

Fishers LSD multiple comparisons

	1	2	3
1 Control	1.00		
2 Light	0.01	1.00	
3 Unburn	0.02	0.26	1.00

Appendix E (continued)

Table E. Mycorrhizal root tips/l by sample period and severity class for Douglas-fir litter.

ANOVA model results

Source	DF	SS	F	P
Model	5	0.36	0.82	0.54
Error	131	11.68		
Total	136	12.04		

Source	DF	SS	F	P
Severity	2	0.11	0.62	0.54
Sample Period	1	0.08	0.87	0.35
Interaction	2	0.04	0.21	0.81

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	control	3	0.00
2	light	0	0.00
3	light	3	0.00
4	unburn	3	0.25
5	control	0	1.16
6	unburn	0	6.40

Table F. Mycorrhizal root tips/l by sample period and severity class for Douglas-fir duff.

ANOVA model results

Source	DF	SS	F	P
Model	5	2.67	1.19	0.32
Error	114	51.34		
Total	119	54.02		

Source	DF	SS	F	P
Severity	2	0.10	0.11	0.89
Sample Period	1	2.49	5.54	0.02
Interaction	2	0.56	0.62	0.54

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	light	3	0.25
2	control	3	3.88
3	unburn	3	4.58
4	control	0	11.33
5	unburn	0	15.24
6	light	0	42.10

Fishers LSD multiple comparisons

	1	2
1 Pre-fire	1.00	
2 Post-fire	0.02	1.00

Appendix E (continued)

Table G. Mycorrhizal root tips/l by sample period and severity class for Douglas-fir shallow mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	5	7.10	3.14	0.01
Error	141	63.85		
Total	146	70.95		

Source	DF	SS	F	P
Severity	2	0.73	0.80	0.45
Sample Period	1	4.59	10.14	<0.01
Interaction	2	4.37	4.83	0.01

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	light	3	19.85
2	control	3	35.13
3	unburn	3	37.16
4	unburn	0	47.96
5	light	0	96.24
6	control	0	113.06

Fishers LSD multiple comparisons

	1	2	3	4	5	6
1 Control pre-fire	1.00					
2 Control post-fire	0.05	1.00				
3 Light pre-fire	0.96	0.09	1.00			
4 Light post-fire	<0.01	0.09	<0.01	1.00		
5 Unburn pre-fire	0.06	0.72	0.11	0.03	1.00	
6 Unburn post-fire	0.12	0.49	0.19	0.01	0.68	1.00

Table H. Mycorrhizal root tips/l by sample period and severity class for Douglas-fir deep mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	5	4.85	2.62	0.03
Error	118	43.70		
Total	123	48.63		

Source	DF	SS	F	P
Severity	2	0.41	0.55	0.58
Sample Period	1	1.31	3.52	0.06
Interaction	2	2.34	3.15	0.05

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	unburn	0	15.51
2	light	0	31.81
3	unburn	3	36.69
4	control	3	41.13
5	control	0	41.47
6	light	3	71.28

Fishers LSD multiple comparisons

	1	2	3	4	5	6
1 Control pre-fire	1.00					
2 Control post-fire	0.42	1.00				
3 Light pre-fire	0.31	0.78	1.00			
4 Light post-fire	0.49	0.18	0.14	1.00		
5 Unburn pre-fire	0.02	0.19	0.40	0.01	1.00	
6 Unburn post-fire	0.76	0.24	0.18	0.63	<0.01	1.00

Appendix E (continued)

Table I. Fine root biomass (g/l) by sample period and severity class for ponderosa pine litter.

ANOVA model results

Source	DF	SS	F	P
Model	6	0.13	0.58	0.75
Error	123	4.57		
Total	129	4.70		
Source	DF	SS	F	P
Severity	3	0.06	0.54	0.66
Sample Period	1	<0.01	0.10	0.75
Interaction	2	0.06	0.80	0.45

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	moderate	3	
2	control	0	0.00
3	light	3	0.00
4	unburn	0	0.26
5	control	3	0.31
6	light	0	0.33
7	moderate	0	0.38
8	unburn	3	1.38

Table J. Fine root biomass (g/l) by sample period and severity class for ponderosa pine duff.

ANOVA model results

Source	DF	SS	F	P
Model	6	0.29	0.43	0.87
Error	87	9.70		
Total	93	9.98		
Source	DF	SS	F	P
Severity	3	0.21	0.64	0.59
Sample Period	1	0.06	0.53	0.47
Interaction	2	0.15	0.66	0.52

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	moderate	3	
2	light	3	0.00
3	moderate	0	0.54
4	light	0	0.72
5	control	0	1.51
6	unburn	0	1.56
7	unburn	3	1.85
8	control	3	3.10

Appendix E (continued)

Table K. Fine root biomass (g/l) by sample period and severity class for ponderosa pine shallow mineral soil.

ANOVA nodel results

Source	DF	SS	F	P
Model	7	0.63	1.70	0.11
Error	146	7.81		
Total	153	8.44		

Source	DF	SS	F	P
Severity	3	0.04	0.23	0.87
Sample Period	1	0.49	9.25	<0.01
Interaction	3	0.16	0.98	0.40

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	moderate	3	0.79
2	light	3	1.02
3	control	3	1.38
4	control	0	1.43
5	light	0	1.86
6	unburn	0	1.91
7	moderate	0	2.09
8	unburn	3	2.54

	1	2
1 Pre-fire	1.00	
2 Post-fire	<0.01	1.00

Table L. Fine root biomass (g/l) by sample period and severity class for ponderosa pine deep mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	7	0.13	0.47	0.86
Error	114	4.56		
Total	121	4.69		

Source	DF	SS	F	P
Severity	3	0.01	0.08	0.97
Sample Period	1	<0.01	0.08	0.78
Interaction	3	0.12	1.01	0.39

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	unburn	3	1.73
2	control	0	1.77
3	light	0	2.02
4	moderate	0	2.04
5	light	3	2.09
6	unburn	0	2.28
7	moderate	3	2.35
8	control	3	3.68

Appendix E (continued)

Table M. Mycorrhizal root tips/l by sample period and severity class for ponderosa pine litter.

ANOVA model results

Source	DF	SS	F	P
Model	6	0.20	0.32	0.92
Error	123	12.98		
Total	129	13.81		

Source	DF	SS	F	P
Severity	3	0.02	0.07	0.97
Sample Period	1	<0.01	0.05	0.83
Interaction	2	0.16	0.78	0.46

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	moderate	3	
2	control	0	0.00
3	light	3	0.00
4	moderate	0	0.00
5	light	0	0.79
6	unburn	3	0.86
7	unburn	0	4.11
8	control	3	13.06

Table N. Mycorrhizal root tips/l by sample period and severity class for ponderosa pine duff.

ANOVA model results

Source	DF	SS	F	P
Model	6	2.57	0.99	0.44
Error	87	37.73		
Total	93	40.28		

Source	DF	SS	F	P
Severity	3	0.66	0.51	0.68
Sample Period	1	0.35	0.81	0.37
Interaction	2	1.12	1.30	0.28

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	moderate	3	
2	light	3	0.00
3	control	0	2.33
4	unburn	3	2.91
5	light	0	8.32
6	moderate	0	10.71
7	unburn	0	19.37
8	control	3	183.52

Appendix E (continued)

Table O. Mycorrhizal root tips/l by sample period and severity class for ponderosa pine shallow mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	7	20.22	5.06	<0.01
Error	146	83.42		
Total	153	103.65		

Source	DF	SS	F	P
Severity	3	5.24	3.05	0.03
Sample Period	1	11.28	19.74	<0.01
Interaction	3	3.34	1.95	0.12

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	light	3	4.52
2	moderate	3	12.30
3	moderate	0	37.89
4	control	3	50.20
5	unburn	0	51.95
6	unburn	3	65.68
7	light	0	73.47
8	control	0	123.53

Fishers LSD multiple comparisons

	1	2	3	4	5	6	7	8
1 Control pre-fir	1.00							
2 Control post-fi	0.01	1.00						
3 Light pre-fire	0.14	0.24	1.00					
4 Light post-fire	<0.01	0.01	<0.01	1.00				
5 Mod pre-fire	0.39	0.26	0.81	<0.01	1.00			
6 Mod post-fire	0.01	0.43	0.11	0.20	0.12	1.00		
7 Unburn pre-fir	0.04	0.29	0.78	<0.01	0.64	0.12	1.00	
8 Unburn post-fi	<0.01	0.96	0.18	<0.01	0.22	0.43	0.20	1.00

Table P. Mycorrhizal root tips/l by sample period and severity class for ponderosa pine deep mineral soil.

ANOVA model results

Source	DF	SS	F	P
Model	7	6.05	1.90	0.07
Error	114	51.81		
Total	121	57.86		

Source	DF	SS	F	P
Severity	3	3.53	2.59	0.06
Sample Period	1	0.03	0.06	0.80
Interaction	3	1.80	1.32	0.27

Adjusted means ranked from smallest to largest

rank	severity	sample per	mean
1	moderate	3	25.13
2	light	3	27.44
3	light	0	36.23
4	control	0	42.55
5	unburn	0	54.96
6	control	3	68.06
7	unburn	3	68.93
8	moderate	0	69.72

Appendix F. Pearson's correlation matrices for pre-fire comparisons

Table A. Pearson's correlation matrix for pre-fire fine root biomass and mycorrhizal densities in Douglas-fir plots. Bold indicates the value is significantly greater then 0 at (p=0.05). Significance does not imply a meaningful comparison is being made.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Depth of Litter (cm)	1													
2. Depth of Duff (cm)	0.07	1												
3. Bulk Density Duff	0.04	-0.2	1											
4. Live Roots (g/L) Duff*	-0.01	**0.26**	0.06	1										
5. Mycorrhizae/L Duff*	-0.04	0.23	**0.24**	**0.42**	1									
6. Bulk Density SMS	0.04	**0.23**	0.08	0.01	0.12	1								
7. Live Roots (g/L) SMS*	0.12	**0.33**	-0.06	**0.38**	**0.26**	0.03	1							
8. Mycorrhizae/L SMS*	0.07	0.01	0.15	0.13	**0.26**	0.17	**0.29**	1						
9. Rock Weight/L SMS	-0.17	**0.25**	-0.06	0.11	0.05	**0.58**	-0.06	-0.02	1					
10.Bulk Density DMS	-0.10	0.21	-0.08	-0.02	0.00	0.21	0.04	-0.12	0.10	1				
11.Live Roots (g/L) DMS*	0.05	0.00	-0.06	0.23	0.07	**-0.27**	**0.29**	0.02	-0.13	-0.17	1			
12.Mycorrhizae/L DMS*	-0.01	-0.09	0.17	-0.11	-0.05	-0.08	**-0.47**	0.19	0.06	-0.18	-0.06	1		
13.Rock Weight/L DMS	-0.12	**0.31**	-0.20	-0.02	-0.03	**0.34**	0.01	-0.24	**0.60**	**0.59**	**-0.31**	-0.13	1	
14.Total Organic Depth	**0.66**	**0.80**	-0.19	0.22	0.13	0.19	**0.33**	0.07	0.09	0.12	0.01	-0.16	0.19	1

*Log Transformation

Appendix F (continued)

Table B. Pearson's correlation matrix for pre-fire fine root biomass and mycorrhizal densities associated with ponderosa pine plots. Bold indicates the value is significa
greater then 0 at (p=0.05). Significance does not imply a meaningful comparison is being made.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Depth of Litter (cm)	1													
2. Depth of Duff (cm)	0.19	1												
3. Bulk Density Duff	0.03	**-0.43**	1											
4. Live Roots (g/L) Duff*	-0.12	-0.04	**0.29**	1										
5. Mycorrhizae/L Duff*	0.16	0.19	0.00	**0.44**	1									
6. Bulk Density SMS	0.17	0.02	-0.03	-0.18	-0.19	1								
7. Live Roots (g/L) SMS*	0.16	-0.01	0.19	**0.47**	**0.27**	-0.08	1							
8. Mycorrhizae/L SMS*	0.13	-0.02	0.11	-0.09	-0.14	0.00	0.14	1						
9. Rock Weight/L SMS	0.09	-0.08	0.03	-0.11	0.03	**0.39**	0.04	0.09	1					
10.Bulk Density DMS	-0.15	0.18	-0.08	0.02	0.17	0.21	0.02	-0.01	**0.30**	1				
11.Live Roots (g/L) DMS*	-0.12	-0.01	0.10	**0.28**	-0.04	-0.13	**0.44**	0.03	0.00	0.14	1			
12.Mycorrhizae/L DMS*	0.13	0.06	0.16	-0.20	**-0.33**	0.21	**-0.26**	0.23	0.10	-0.09	0.08	1		
13.Rock Weight/L DMS	-0.19	-0.18	0.20	0.03	-0.05	0.20	0.07	0.03	**0.71**	**0.63**	0.10	-0.02	1	
14.Total Organic Depth	0.60	0.91	**-0.35**	-0.08	0.23	-0.02	0.17	0.19	0.02	0.04	-0.06	0.04	-0.23	1

*Log Transformation

Appendix G. Pearson's correlation matrices for post-fire comparisons

Table A. Pearson's correlation matrix for reduction of fine root biomass and mycorrhizal densities for Douglas-fir. Bold indicates the value is significantly greater then 0 at (p=0.05). Significance does not imply a meaningful comparison is being made. N=14.

	1	2	3	4	5	6	7	8	9	10	11	12
1) Bulk Density (pre-fire)	1											
2) Bulk Density (post-fire)	-0.19	1										
3) Live Roots (g/L)* SMS (pre-fire)	0.04	-0.10	1									
4) Mycorrhizae/L* SMS (pre-fire)	0.30	0.17	0.10	1								
5) Rock Weight/L*	0.47	0.07	0.27	0.35	1							
6) Live Roots (g/L)* SMS (post-fire	0.24	0.49	0.47	-0.00	0.42	1						
7) Mycorrhizae/L SMS* (post-fire)	0.29	0.43	0.24	-0.11	**0.62**	**0.65**	1					
8) Total Organic Reduction (cm)	0.26	-0.21	0.27	0.34	0.44	0.01	0.07	1				
9) Residual Organic Depth (cm)	0.45	0.26	0.49	0.07	**0.53**	**0.95**	**0.62**	0.09	1			
10)Soil Moisture SMS	-0.31	0.11	0.45	-0.07	-0.37	0.28	-0.35	0.05	0.15	1		
11)Live Root (g/L) Reduction	-0.02	-0.36	**0.88**	0.10	0.07	0.04	-0.03	0.27	0.09	0.37	1	
12)Mycorrhizae/L Reduction	0.11	0.19	0.06	**0.81**	0.34	-0.10	-0.13	0.48	-0.09	-0.06	0.06	1

*Log Transformation

Appendix G (continued)

Table B. Pearson's correlation matrix for reduction of fine root biomass and mycorrhizal densities for ponderosa pine. Bold indicates the value is signifi greater then 0 at (p=0.05). Significance does not imply a meaningful comparison is being made. N=14.

	1	2	3	4	5	6	7	8	9	10	11	12
1) Bulk Density (pre-fire)	1											
2) Bulk Density (post-fire)	0.34	1										
3) Live Roots (g/L)* SMS (pre-fire)	-0.15	-0.03	1									
4) Mycorrhizae/L* SMS (pre-fire)	-0.20	-0.05	**0.45**	1								
5) Rock Weight/L*	0.20	0.14	0.35	0.02	1							
6) Live Roots (g/L)* SMS (post-fire)	0.14	0.11	0.08	0.06	-0.18	1						
7) Mycorrhizae/L SMS* (post-fire)	0.02	0.18	0.03	0.15	0.08	**0.47**	1					
8) Total Organic Reduction (cm)	-0.19	0.12	0.30	**0.43**	-0.00	-0.29	0.01	1				
9) Residual Organic Depth (cm)	0.34	0.04	-0.02	-0.06	-0.03	**0.93**	0.34	**-0.44**	1			
10)Soil Moisture SMS	0.04	0.00	0.09	0.18	-0.09	0.13	-0.18	-0.06	0.08	1		
11)Live Root (g/L) Reduction	-0.08	0.05	**0.63**	0.26	0.27	**-0.65**	-0.31	**0.48**	**-0.72**	0.05	1	
12)Mycorrhizae/L Reduction	-0.06	-0.16	0.15	**0.66**	-0.10	-0.15	-0.18	0.25	-0.12	0.17	0.16	1

*Log Transformation