Project Title: Impacts of Post-Fire Salvage Logging and Wildfire Burn Intensity on Soil Productivity and Forest Recovery

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I. Abstract

This project consists of two interrelated studies designed to determine how soil productivity responds to 1) post-fire salvage logging, and 2) soil burn severity in a mixed conifer forest. The project was conducted within the perimeter of the Booth and Bear Butte (B&B) Fire Complex, a large stand-replacing wildfire that burned over 36,730 hectares in the summer of 2003. In study one, we examined the effects of salvage logging operations (e.g. compaction, subsoiling) on soil productivity on 7 replicate sites, harvested 1 year after the B&B fire. Within each site, we measured the impacts of 3 treatments (burning with no further disturbance, compaction from heavy equipment, and compaction followed by subsoiling) on soil biological, chemical, and physical properties critical to soil productivity and growth of planted tree seedlings. Post-fire salvage logging, frequently conducted in forests to recover economic value of burned timber killed by wildfire, may reduce burn severity of soils in the event of a future fire in areas with large amounts of dead wood.

Post B&B fire surveys indicate that severely burned soils occurred on 3 to 19% of the forest floor, with higher percentages in areas that contained large down wood from previous fires or insect attack. Exposure of soil to severe heating during a wildfire volatilizes soil nutrients and causes mortality of microbial communities. In study two, we examined the effects of burn severity on soil microbial communities, soil nutrients and soil physical properties to determine the recovery of soils after severe wildfire. Preliminary soil samples were collected immediately after containment of the B&B fire and prior to rainfall that may have induced soil movement. In spring 2004, the study was expanded to include a total of 5 stands (blocks) within the perimeter of the fire where significant percentages of severely burned soils accompanied significant tree mortality due to stand replacing wildfire. At each of the 5 stands, paired plots were established that included soils from severely burned soil and adjacent moderately burned black soil.

The effects of salvage logging operations and burn intensity on soil productivity and forest recovery are poorly understood. Findings from this research provide knowledge critical to successful recovery projects on the B&B and other fire sites in mixed conifer forests throughout central Oregon.

II. Background and Purpose

Low temperature fire plays an important role in maintaining forest ecosystems by removing dead and accumulated vegetation and quickly releasing nutrients bound in litter, thus enriching the soil. Exclusion of frequent, low-intensity fire has significantly altered stand dynamics in our project area. *Abies concolor* and *Abies grandis* which are less fire resistant than *Pinus ponderosa* or *Pseudotsuga menziesii* historically were removed or reduced in stands by frequent fire. The proportional increase of *Abies concolor* and *Abies grandis* has increased ladder fuels and the threat of stand-replacing wildfires.

The 2003 Booth and Bear Butte Fires, collectively known as the B&B Complex Fire, burned over 36,730 hectares, creating a mosaic of forest disturbance in the Deschutes and Willamette National Forests, Mt. Jefferson Wilderness, and the Warm Springs Reservation in central Oregon. Excessive fuels and high stand densities contributed to intense fire behavior, increased resistance to control, and the loss of critical late succession wildlife habitat. In certain areas of the B&B Fire, large amounts of down wood from previous wildfire or insect and disease mortality contributed to increased fire intensity and significantly higher percentages of detrimentally burned soil compared to other burned areas. In addition, the B&B Fire created areas with large amounts of standing dead timber, placing areas at risk of high percentages of detrimentally burned soil in the likely event of a future fire. The impact of the fire and post-fire management activities on the belowground ecosystem is of special concern to future forest recovery. Post-fire salvage logging provides economic gain and, by removing large dead wood, may reduce burn severity of soils in the event of reburning (Poff 1989). This project consists of two interrelated studies designed to determine how soil nutrient levels and soil productivity respond to 1) post-fire salvage logging and 2) burn severity in a mixed conifer forest.

This project was developed in response to concerns expressed by forest managers about the impact of salvage logging operations and reburning on soil productivity. These concerns were a key point of discussion at the B&B Fire Dead Wood Workshop (May 19, 2004) held at the Shiloh Inn in Bend, OR and at the PNW Current Issues Meeting between the B&B Interdisciplinary Team and PNW Scientists (October 26, 2004) held at the Sisters Ranger District in Sisters, OR. The objectives for this project, focusing on soil dynamics and productivity, were consistent with the highest priorities voiced by the resource managers.

Assessment of the ecological costs and benefits of post-fire salvage operations is critical to the intelligent use of management activities and resources (McIver and Starr 2000). The effects of salvage logging and burn severity on basic ecosystem processes and site productivity are poorly understood. Fire and post-fire logging affects abundance and composition of fungal and bacterial communities which in turn causes changes in nutrient cycling. Changes in soil microbial communities, respiration, and nutrient availability affect ecosystem recovery. Soil microbes are critical to improved conifer tree and seedling growth, and to symbioses resulting in atmospheric nitrogen-fixation by certain understory plants. Nutrient availability is strongly linked to pH and cation exchange capacity (CEC). Intense fires can affect soil mineralogy, significantly altering CEC (Brady and Weil 2002).

Numerous factors affect the ecosystem impacts of fire and logging and it is often difficult to apply the results of studies from distant locations to local conditions. The objectives for this project were to provide knowledge critical to understanding the effects of post-fire salvage logging and burn severity on soil productivity in mixed conifer forests with sandy loam soils in central Oregon.

Specifically the objectives were to:

1. Determine the effects of post-fire salvage logging (e.g. compaction, subsoiling) on soil chemical, physical, and biological properties.
2. Determine the effects of compaction and subsoiling on tree seedling growth of two species planted after harvesting.
3. Assess the recovery and determine if there are differences in soil microbial community composition between severely burned soils and less severely burned soils.
4. Determine whether there are differences in soil chemical and physical properties between the two burn severities.
5. Effectively transfer knowledge gained from these studies to resource managers, scientists, and the public.

III. Study Description and Location

This project was conducted on the eastern slope of the Cascade Range of Oregon in the Deschutes National Forest. The Cascade Mountains create a barrier to marine air masses from the Pacific Ocean resulting in the east slope being comparatively drier than the west slope. The eastside of the Oregon Cascade Mountains exhibits some of the steepest moisture gradients in the world and a large diversity of tree species. Our study area is characterized by a mixed conifer forest with an overstory of *Pinus ponderosa* C. Lawson, *Pseudotsuga menziesii* (Mirb.) Franco., *Abies concolor* (Gord. & Glend.) Lindl. Ex Hildebr., *Abies grandis* (Dougl. ex D. Don) Lindl., *Pinus monticola* Dougl. ex D. Don, and *Larix occidentalis* Nutt., and an understory of *Ceanothus velutinus* Dougl., *Rosa gymnocarpa* Nutt., *Symphoricarpos albus* (L.) Blake, *Berberis nervosa* Pursh, *Rubus ursinus* Cham. & Schlecht and *Vaccinium parvifolium* Sm. (Simpson 2007). Most stands in the study belong to the *Abies concolor - Abies grandis* plant classification series as described by Simpson (2007) with *Pseudotsuga menziesii* or *Pinus ponderosa* or both, typically dominating the overstory canopy. Soils are Aquic Vitrixerands and Alfic Vitrixerands with sandy-loam texture. Elevations of stands range in the salvage-logging study from 950–1030 m and in the fire severity study from 1000–1300 m. Average temperatures range from -1 ºC in the winter months to 20 ºC in the summer months. Average annual precipitation ranges from 50–150 cm. About 70% of the precipitation falls during November through April. During the driest months (July, August, and September), the average monthly precipitation is less than 2.5 cm.

Study 1: Salvage Logging

Timber sales approved prior to the B&B fire, and subsequently harvested one year after the fire, provided a unique and timely opportunity to study the impacts of post-fire salvage logging. Salvage logging and subsoiling occurred in summer 2004. Subsoiling was completed on all stands within a 3-day period. Subsoiling, or deep tillage, is employed to decrease soil bulk density, thereby improving aeration and infiltration (Otrosina et al. 1996). Stands ranged in size from 5–13 hectares and were thinned from below with feller bunchers.

The study was a randomized complete block design with 7 post-fire salvage logged stands (blocks) and 3 treatments: burning with no further disturbance (undisturbed), compaction from heavy ground-based equipment (compacted), and compaction followed by subsoiling (subsoiled). A 4–6 m grid system was established on each stand; all grid points were marked with a stake and recorded with GPS. A 10 m buffer zone within the perimeter of each stand was not sampled to avoid potential edge effects. Compacted and subsoiled treatments were identified based on visual indications of equipment use. Within each stand, 3 grid points (plots) were randomly selected from each treatment for sampling soil chemical, physical, and biological properties and tree seedling growth. In total, there were 7 replicate stands with 3 treatments each and 3 plots of each treatment, for a total of 63 plots; each plot was sampled over 7 seasons: summer 2005, fall 2005, spring 2006, summer 2006, fall 2006, spring 2007, and summer 2007, for variables indicated in Table 1.

Table 1: Response variables measured for each stand in the salvage logging study.

	2005		2006			2007	
Response variable	Summer	Fall	Spring	Summer	Fall	Spring	Summer
Chemical							
CEC	3[a]			3[a]			3[a]
%OM (LOI)	3[a]	3[a]	3[a]	3[a]	3[a]	3[a]	
C:N	3[a]			3[a]			3[a]
pH	3[a]			3[a]			3[a]
Total C	3[a]			3[a]			3[a]
Total N	3[a]			3[a]			3[a]
Net mineralizable N	3[a]			3[a]			
Net mineralizable NH_4							3[a]
Net NH_4	3[a]			3[a]			3[a]
Net NO_3-N	3[a]			3[a]			3[a]
Anaerobic incubation NH_4-N	3[a]			3[a]			3[a]
Total P							3[a]
Available P	3[a]			3[a]			3[a]
Physical							
Texture	1[b]						
Moisture	3[a]	3[a]	3[a]	3[a]	3[a]	3[a]	
Bulk density		1[c]	1[c]			1[c]	
Biological							
Respiration	3[b]	3[b]	3[b]	3[b]	3[b]	3[b]	
Bacterial species richness	3[b]	3[b]	3[b]	3[b]	3[b]	3[b]	
Fungal species richness	3[b]	3[b]	3[b]	3[b]	3[b]	3[b]	
Bacterial functional diversity						3[a]	
Phosphatase activity						3[a]	
Tree growth response							
PIPO height	15[b]						15[b]
PIPO caliper	15[b]						15[b]
PSME height	15[b]						15[b]
PSME caliper	15[b]						15[b]

[a] combined samples within treatments x stand $^{-1}$
[b] treatment x stand^{-1}
[c] selected stake x treatment^{-1} x stand^{-1}

Study 2: Fire Severity

Small areas of soil associated with the complete combustion of large pieces of decaying wood or stumps in direct contact with the soil can be found scattered throughout burned areas. These severely burned soils show a distinctive color change where the top layer of mineral soil changes to various shades of red due to excessive heating and oxidation of the soil matrix. These severely burned, reddened sites are commonly found as long, narrow, linear strips ranging from 0.6–3 m or more long, and 5–35 cm wide that were created as decaying logs were consumed by fire. They also can be found as deep, irregular patches often 90 cm or more in diameter, where stumps and root systems were consumed by fire (Shank 2004). In our study area, red soils were observed on 3–19% of the forest floor, with higher percentages in areas that contained large down wood from previous fires (Shank 2004). Smoldering conditions that create red soils volatilize soil nutrients, reducing nutrient availability and plant growth in the short or long term (Neary et al.1999). No research, to our knowledge, has been conducted on soil chemistry and soil microbial and plant communities in naturally occurring wildfire-induced red soils. There is a critical need to determine the recovery rate of soils after severe wildfire, including microbial population size, activity, and composition, and soil nutrient pools.

Twelve paired samples of severely burned red soils and less severely burned black soils were taken in October 2003 in the Jefferson Wilderness, Deschutes National Forest. These preliminary soil samples were collected immediately after containment of the B&B fire and prior to rainfall that may have induced soil movement. In spring 2004, the study was expanded to include a total of 5 stands (blocks) within the perimeter of the fire where significant percentages of severely burned soils accompanied significant tree mortality due to stand replacing wildfire. At each of the 5 stands, 3–6 paired plots were established that included soils from severely burned red soils and adjacent moderately burned black soil (< 2 m distance). Soil samples to determine fungal and bacterial species richness were collected in spring, summer, and fall of 2004 and 2005. In summer 2004, a subset of 10 paired plots, with at least one paired plot per stand, was randomly selected for soil chemistry as part of a complementary study by Hebel et al. (2009). With funding from this grant, sampling continued on the same schedule as shown in Table 1. Response variables measured were similar to those listed in Table 1. Additionally percent vegetation cover was recorded 2 years post-fire for the 10 paired black and red soil plots. Soil samples for both fungal and bacterial species richness and soil chemistry were collected from the top 10 cm of soil. Soil was transported to the lab and stored at $^{-}$80 °C for DNA extraction, $^{-}$20 °C for phospholipid fatty acid (PLFA analysis) and at 4 ºC for soil chemistry analysis.

A combination of methods in both studies characterized the impact of post-fire salvage logging and burn severity on soil microbial communities. Methods included PCR-based molecular techniques to assess species richness and community composition, PLFA analysis to detect the presence and abundance of broad microbial groups, and community level physiological profiles (CLPP) to assess functional diversity.

IV. Key Findings

Study 1: Salvage Logging

Soil microbial communities

- Compaction and subsoiling after post-fire salvage logging had little effect on soil bacterial and fungal species richness and function. These findings suggest that soil bacteria and fungi in these post-fire landscapes are tolerant of the occurrence of fires and resilient to certain types of disturbance. The average cumulative number of bacterial and fungal species did not differ among treatments. For soil bacteria, a consistent trend showed a greater average cumulative number of species in the compacted soil than in either the undisturbed or subsoiled treatments (Fig. 1). Similarly, for soil fungi the average cumulative number of species was either greatest in the compacted soil or similar to the average cumulative number of species in the undisturbed soil. The trend of greater mean cumulative number of bacterial and fungal species in the compacted soil treatment may indicate slightly favorable conditions and less predation by microbivores on the bacterial and fungal communities. Soils in this study, developed on Mazama ash, may benefit from compaction perhaps by holding more water. Functional diversity, measured for bacteria, did not differ among treatments.

- Neither the mean number of bacterial nor fungal species differed by treatment. However, a significant decrease in the mean number of bacterial species was seen after the spring 2006 sampling and a significant increase in the mean number of fungal species occurred in the spring 2007 sampling. These findings suggest that time since fire has a greater impact on bacterial species richness than does logging disturbance in the sandy loam soils of our study area. These findings also suggest that environmental factors (e.g. rainfall, temperature, etc.) have a greater impact on the fungal species richness than time since fire or logging disturbance. Bacterial and fungal community composition did not differ among treatments.

Soil properties

- Total P was lower in the subsoiled and compacted treatments than in the undisturbed treatment. Plant available P was lower in the subsoiled treatment than in the undisturbed or compacted treatments. Incubation N and net mineralizable N both were lower in the compacted treatment than in the undisturbed treatment. Total C and Total N did not differ among treatments. See Table 2 for values. Decreased plant available P and N after post-fire salvage logging could have long lasting effects in a nutrient limited system.

Fig. 1. Cumulative mean number of T-RFLP bacterial species by season and treatment.

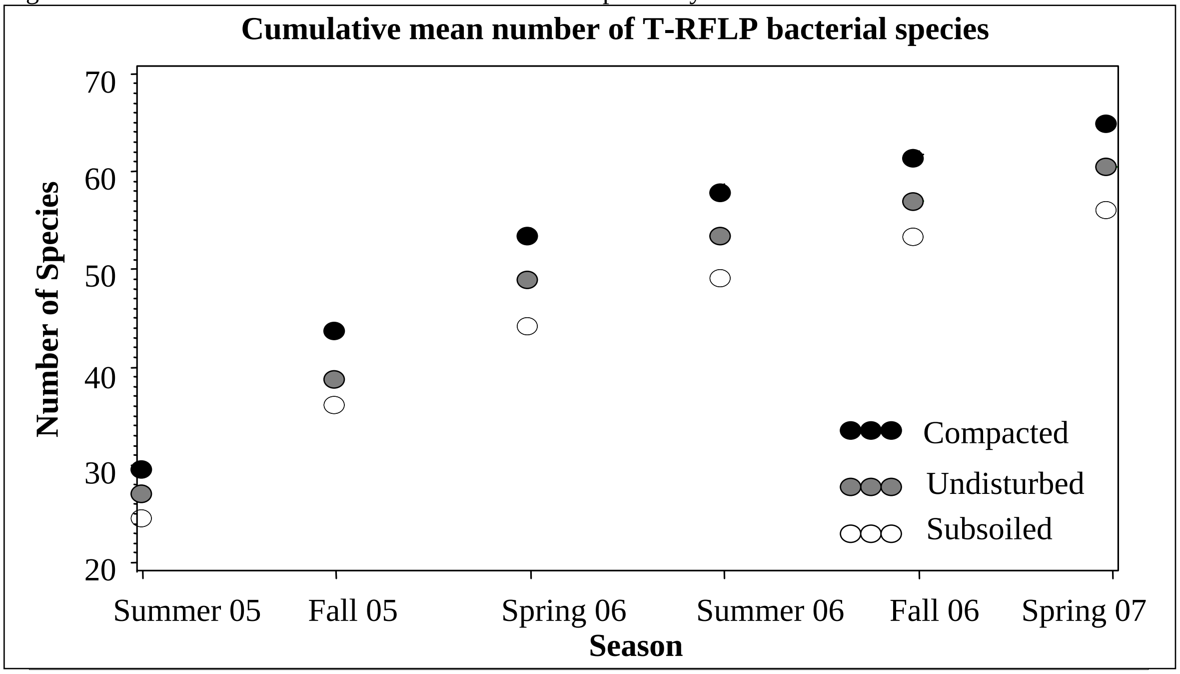


Table 2. Soil chemical and biological properties.

Treatment	Total C	Total N	N min. 2007 (ppm)	Inc. N (ppm)	Total P (ppm)	P-Bray (ppm)	Respiration (µmol $m^{-2}s^{-1}$)
Compacted	3.15[a] (0.23)	0.16[a] (0.01)	28.11[a] (2.92)	29.51[a] (3.23)	1189.53[a] (66.72)	9.57[a] (0.85)	2.45[a] (0.12)
Subsoiled	3.02[a] (0.24)	0.16[a] (0.01)	32.73[a,b] (4.65)	35.19[a,b] (4.95)	1152.09[a] (79.99)	7.29[b] (0.39)	2.36[a] (0.12)
Undisturbed	3.15[a] (0.20)	0.16[a] (0.01)	38.03[b] (4.82)	40.47[b] (4.83)	1296.25[b] (74.35)	9.81[a] (0.82)	2.93[b] (0.14)
$F_{[df,df]}$	$0.13_{[2,12]}$	$0.07_{[2,12]}$	$6.53_{[2,12]}$	$6.65_{[2,12]}$	$2.86_{[2,12]}$	$13.5_{[2,12]}$	$3.24_{[2,42]}$
p	0.88	0.93	**0.01**	**0.01**	**0.1**	**0.001**	**0.05**

Note: Data are averaged across years. Within a column, means with a common lowercase letter are not significantly different at p < 0.1. Means are listed with standard errors in parentheses. Bolded p values indicate a significant difference at p < 0.1.

Vegetation

- Subsoiling positively affected tree seedling survival and growth of out-planted ponderosa pine and Douglas-fir seedlings. The median percent survival and median height growth in subsoiled plots was significantly higher than in compacted and undisturbed plots for both tree species. The median diameter growth of ponderosa pine in subsoiled plots was significantly higher than in compacted and undisturbed plots. The median diameter growth of Douglas-fir in subsoiled plots was significantly higher than in undisturbed plots, but did not differ between subsoiled and compacted plots. See Table 3 for values.

Table 3. Survival and growth of out-planted ponderosa pine (PIPO) and Douglas-fir (PSME) seedlings.

Treatment	**PIPO Median % Survival**	**PSME Median % Survival**	**PIPO Median Height**	**PSME Median Height**	**PIPO Median Diameter**	**PSME Median Diameter**
Compacted	73.26[b] (5.65)	43.32[b] (17.00)	18.59[b] (1.31)	13.26[b] (1.47)	4.10[b] (0.34)	4.17[a] (0.42)
Subsoiled	88.41[a] (3.40)	73.40[a] (14.89)	27.91[a] (1.59)	21.93[a] (2.23)	7.23[a] (0.54)	5.02[a] (0.52)
Undisturbed	61.40[b] (9.98)	29.46[b] (11.98)	12.47[b] (1.16)	10.00[b] (1.57)	1.93[b] (0.19)	2.32[b] (0.38)
$F_{[df,df]}$	$9.09_{[2,10]}$	$6.38_{[2,10]}$	$42.26_{[2,10]}$	$19.09_{[2,10]}$	$50.01_{[2,10]}$	$19.09_{[2,10]}$
p	**0.005**	**0.02**	**0.0001**	**0.0004**	**0.0001**	**0.0004**

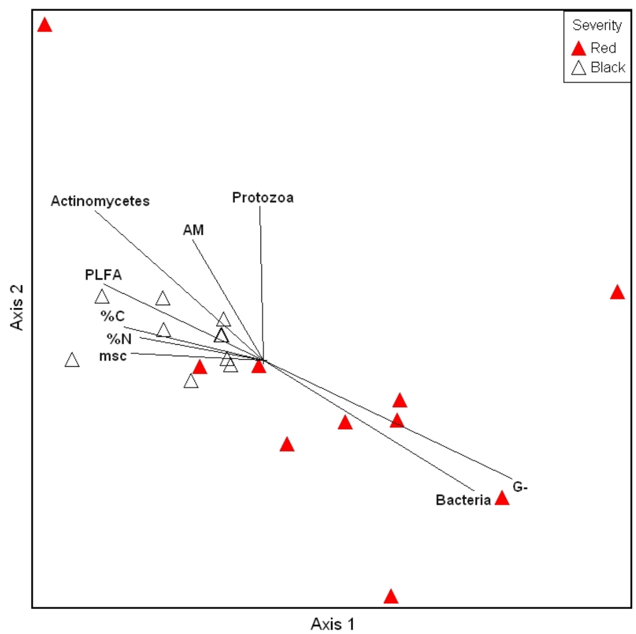
Note: Within a column, medians or means with a common lowercase letter are not significantly different at $p < 0.05$. Medians and means are listed with standard errors in parentheses. Bolded p values indicate a significant difference at $p < 0.05$.

Study 2: Fire Severity

Soil microbial communities

- Soil burn severity was the most important factor influencing microbial community structure in the first two years after fire. Severely burned red soils have long been thought to be "sterilized" by fire and absent of biological activity. Our preliminary study showed that severely burned red soils were initially greatly reduced of microbes, but were not sterile. Two years after fire, mean fungal species richness remained significantly less in the severely burned soils compared to the moderately burned soils. Results of the PLFA analysis showed that the soil microbial communities of severely burned red soil differed from moderately burned black soil (Fig. 2). Severe soil heating as well as loss of organic matter increased the mortality of all soil microbial groups in red soils. Four years after fire there was no difference in the cumulative mean number or mean number of fungal or bacterial species between burn severities. Fungal and bacterial community composition of the burn severities did not differ four years after the fire even though some species were detected only in red or black soils. However, community level physiological profiles (Biolog ecoplates) detected a difference in the functional diversity of bacteria between burn severities nearly four years after fire (spring 2007).

Fig. 2. NMS ordination of PLFA relative abundance by burn severity. Symbols represent the microbial community of freshly collected soil from each plot separated by burn severity. R^2 axis 1 = 0.84, axis 2 = 0.058. Vectors are based on summed abundances of specific PLFA groups and environmental variables. The length of the vector is proportional to the correlation between that variable and the NMS axis.



Soil properties

- One year after fire, soil pH was highest in red soil, while soil P, net NO_3-N, anaerobic incubation N, net mineralizable N, CEC, and total C and N all were highest in black soil (Table 4). The severe loss of organic matter in red soil resulted in 71 % less soil C than in black soil, strongly contributing to the microbial community differences between red and black soil. Similarly, total N and plant available P of red soils was 69 % and 71 % less respectively than in black soil. Four years after fire, pH remained highest in red soil; net NO_3-N, net mineralizable N, CEC, plant available P, and total C and N all remained highest in black soil; percent moisture, and respiration did not differ between burn severities (Fig. 3).

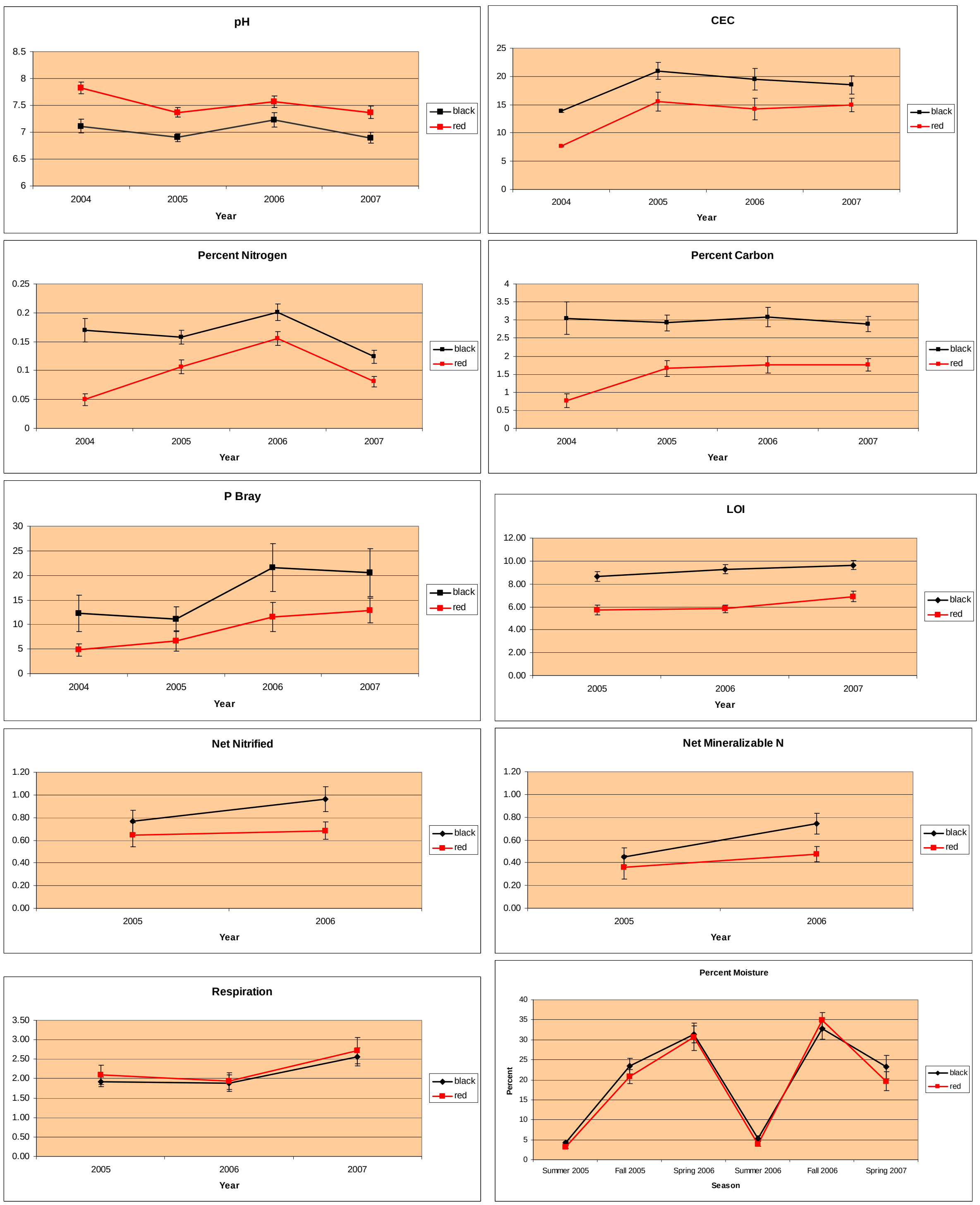
Table 4. Paired t-test of differences in soil chemistry between two burn severities one year after fire. Bolded text indicates a significant difference between means (α = 0.05). SE denoted in parentheses (n = 10).

Response variable	Severity	Mean	t_9	*P*-value
pH	Red Black	7.9 (0.06) 7.3 (0.08)	5.18	**< 0.001**
Available P (ppm)	Red Black	3.5 (0.36) 12.2 (2.5)	-3.43	**0.007**
Extractable NO_3-N (ppm)	Red Black	1.4 (0.36) 4.3 (1.1)	-2.48	**0.035**
Initial extractable NH_4-N (ppm)	Red Black	36.7 (10.1) 45.3 (10.6)	-1.40	0.193
Anaerobic incubation NH_4-N (ppm)	Red Black	44.5 (11.3) 73.6 (12.5)	-3.48	**0.006**
Net mineralizable NH_4-N (ppm)	Red Black	7.7 (1.6) 28.3 (2.7)	-6.66	**< 0.001**
CEC ($cmol_c$ kg^{-1})	Red Black	9.4 (1.3) 18.3 (2.0)	-5.29	**< 0.001**
Total C (%)	Red Black	1.0 (0.16) 3.5 (0.29)	-8.16	**< 0.001**
Total N (%)	Red Black	0.04 (0.01) 0.13 (0.01)	-7.90	**< 0.001**

Vegetation

- Our findings indicate that burn severity influences microbial dynamics and soil nutrient availability; each of these factors affects plant initiation and development in burned areas. Vegetation surveys two years post-fire revealed that percent cover was more than 51% less on severely burned red soil plots compared to less severely burned black soil plots. Net mineralizable N and available soil P were substantially reduced in red soil by 73% and 71%, respectively, possibly contributing to the lower percent cover observed on these soils.

Fig. 3 Soil chemical, physical, and biological properties between burn severities one to four years after fire.



V. Management Implications

- The loss of forests, vital to the sequestration of carbon and the slowing of global warming, is of utmost concern. It is well established that fire is a key disturbance process in most ecosystems, and that low temperature fire maintains forest ecosystems by removing dead and accumulated vegetation and quickly releasing nutrients bound in litter. However, the accumulation of fuels after decades of fire suppression, in addition to a combination of other factors, has contributed to frequent high severity, stand-replacing wildfire events in the western United States. Such fires effect soil microbial dynamics and nutrient availability, contributing to structural changes in the landscape that will likely persist for generations.

- Land managers are faced with balancing the uncertainty about impacts of biomass removal, (e.g. thinning and prescribed fire before wildfire or removal of standing dead timber after wildfire), with the certain outcome of stand-replacing wildfire. The results of these studies, along with the recovery potential of a site, and the impending risk of future wildfire in stands differing in structure from historic conditions, bear consideration when considering post-fire removal of timber. High densities of fire-killed trees after a severe wildfire may increase the area of red soil in the event of a reburn. Understanding how soil microbes, soil nutrients, and vegetation respond to severe wildfire and post-fire salvage logging will assist forest managers in selecting fuel-reducing treatments that maintain critical soil processes.

VI. Relationship to Other Recent Findings and Ongoing Work on This Topic

Recent studies have shown that in the event of wildfire, increased fuel loads have the potential to increase the area of severely burned red soil (Brown et al. 2003). High densities of fire-killed trees after a severe wildfire may also increase the area of red soil in the event of a reburn (Poff 1989, Brown et al. 2003, Shank 2004, Monsanto and Agee 2008). Knowledge of the impact of severe surface burning and post-fire salvage logging on soil nutrients, soil microbial communities and post-fire plant re-colonization is critical to forest recovery projects (Busse et al. 2007).

Study 1: Salvage Logging

In our study, the trend of more mean cumulative number of bacterial and fungal species in the compacted soil treatment may indicate slightly favorable conditions and less predation on those communities. The inability of predators to access small pores in compacted soil may help to stabilize the microbial community (Breland and Hansen 1996). However, protection from predation may benefit community stability at the cost of reducing plant nutrient availability (Busse et al. 2006). Moldenke et al. (2000) found that compaction caused by skid roads in the Deschutes National Forest, contributed to a shift in the foodweb to one that utilizes primarily bacteria; it also reduced the general size categories of inhabitants and shifted their life history toward short-lived species. Khetmalas et al. (2002) found no significant difference in bacterial diversity between burned–salvaged and unburned stands 4–5 yr after fire and salvage-logging. Recent studies also have found that compaction had no effect on microbial community size, activity, function, or structure (Shestak and Busse 2005, Busse et al. 2006).

Microbial community responses to burning and harvesting range from low resilience, as seen in low-severity prescribed burning (Fritze et al. 1993, DeLuca and Zouhar 2000), to high resilience or complete tolerance following intensive forest management (Edmonds et al. 2000, Busse et al. 2001, 2006, Siira-Pietikäinen et al. 2001). Previous studies have found that compaction can have negative (Dick et al. 1988, van der Linden et al. 1989, Torbert and Wood 1992, Breland and Hansen 1996), neutral (Breland and Hansen 1996, Shestak and Busse 2005), or positive (Startsev et al. 1998) effects on microorganisms, and that these effects are likely due to the complexity of soil disturbances.

Salvage logging frequently results in soil compaction, reducing soil pore size and decreasing oxygen availability and movement of water and nutrients to tree roots. To alleviate compaction, the practice of subsoiling is used to fracture the lower strata of soil. In our study subsoiling positively affected tree seedling survival and growth of out-planted ponderosa pine and Douglas-fir seedlings. Survival and growth of seedlings grown in compacted soils did not differ from those grown in burned areas that received no further disturbance. In contrast to our results, Gomez et al. (2002) reported that compaction in sandy loam soils increased the growth of young ponderosa pines compared to those grown on non-compacted coarse-textured soil. Soil compaction may negatively or positively affect ponderosa pine tree growth depending on soil texture (Davis 1992, Page-Dumroese 1993, Gomez et al. 2002). Compaction in clayey soils, which have high water and nutrient retention, produced negative growth responses (Gomez et al. (2002).

Study 2: Fire Severity

Our study is unique in that we investigated the microbial communities, soil chemistry, and plant growth in naturally occurring severely burned red soils, which smoldered much hotter and longer than comparable soil conditions assessed in other studies. Severely burned soil found inside slash pile scars did not show the extreme limitation of nutrients found in red soils examined in our study. For example, Korb et al. (2004) investigated the effects of slash pile burning on soil biotic and chemical properties. They reported an 18%, 20%, and 9% reduction in soil C, N, and P, respectively, inside severely burned slash pile scars from the unburned soil outside the scar. In comparison, the severely burned red soil examined in our study contained 71%, 69%, and 71% less total soil C and N, and less plant available P, respectively, than the less severely burned black soil.

The severe loss of organic matter in red soil strongly contributed to the microbial community differences between red and black soil. These results are consistent with previous findings indicating that substantial changes in soil temperature during heating can result in volatilization of C and soil nutrients, mortality of soil microbes and shifts in species composition of survivors (Bååth et al. 1995, Pietikäinen et al. 2000, Knicker 2007, Bormann et al. 2008).

Microbial dynamics and soil nutrient availability affect plant initiation and development in burned areas. Vegetation surveys two years post-fire revealed that percent cover was more than 50% lower on red soil in all plots. Net mineralizable N and available soil P were substantially reduced in red soil, possibly contributing to the lower percent cover observed on these soils. Other researchers have described the decrease in plant biomass with increasing burn severity for up to 2 yrs post-fire (Feller 2000). Our observations support the hypothesis that red soils will have slower vegetative recolonization because high severity fire degrades more of the plant seed bank and AM fungal propagules, in addition to altering soil nutrient and water availability, thus affecting the post-fire community (Rowe, 1983).

VII. Future Work Needed

Findings from the two studies in this project reflect a relatively short time period since fire, yet lay the foundation for interpreting post-wildfire ecosystem responses and post-fire management responses for lessening the risk of future wildfire resulting in severely burned soils. The extreme effects of fire on soils that we observed in severely burned red soils will likely be long-lasting. Future studies should continue to address recovery of these soils by focusing on microbial communities that drive soil processes and investigating the role of pioneering nitrogen-fixing plants that can help rebuild nutrient pools. Soil biological response to severe fire should continue in order to provide managers with long term results about soil recovery. Four years after fire, soil microbes were observed to be returning to the severely burned soils but soil nutrients remained lower in these soils compared to the less severely burned soils. Future research should include measuring the length of time before soil nutrients (reflecting soil processes) are similar between severely burned and less severely burned soils.

New insights into soils, forest productivity, and diversity in forests with frequent fire-return intervals are likely with continued investigation. Vegetation cover between severely burned and less severely burned soil – measured 2 years after fire in this project – should be measured at a future date to assess continued aboveground recovery. A study investigating tree seedling survival and growth between burn severities would provide further insight about aboveground recovery of severely burned soils and future forest structure of stands with large percentages of severely burned soils. Comparing tree seedling growth between burn severities was attempted in this project. However, high seedling mortality in both burn severities (due to seedlings being planted late in the spring) resulted in insufficient data for analysis.

The question frequently arises about how severely burned soils compare to non-burned areas. Given that the natural historic condition would have included frequent light fires, a more appropriate future research focus would be to compare soil biological, chemical and physical properties, and vegetation, between areas receiving frequent low severity fires and severely burned areas.

The decrease in plant available P and N after post-fire salvage logging in the subsoiled and compacted treatments could have long lasting effects in a nutrient limited system. Future studies should continue to measure tree seedling growth on salvage logged treatments to determine if seedlings planted in the subsoiled treatments continue to outperform seedlings planted in compacted or undisturbed soil treatments. Additionally, respiration rates, total P, plant available P, incubation N and net mineralizable N should continue to be measured in these treatments. It appeared that less vegetation was growing in the compacted and subsoiled salvage logged treatments compared to the undisturbed areas. Measurements of vegetation cover among salvage log treatments should be included in a future study.

Discussions at our workshop/field tour suggest that it will be necessary to continue to communicate the message to the public and environmental groups that management can be based on good science, but that local managers are dealing with a complexity of issues and management objectives. Trust may be gained by encouraging local interest groups to participate in developing local management objectives based on desired forest structure and ecological functions. Gaining support for adaptive management, the process of learning by doing and incorporating new information into management as it is learned, may elicit participation in planning rather than negative response to proposed forest plans. In addition to adaptive management, replicated, statistically sound studies are needed.

VIII. Deliverables Crosswalk Table

Proposed	Delivered	Status
Presentations at National & International Meetings	See JFSP website and additional reporting below (currently 22 meeting/conference presentations)	Completed (posted on JFSP website)
Refereed publications	See JFSP website and additional reporting below (currently includes 2 articles in print, 1 proceedings on CD, 2 masters theses, and 5 papers in preparation)	Completed documents posted on the JFSP website
Workshops & Field Tours	(1) Two pre-proposal field tours were conducted in Fall 2004 to discuss preliminary findings (2) Met with land managers at Deschutes NF, Sisters RD to present progress of this JFSP project (15 participants) April 11, 2006 (3) Knowledge Transfer -- B&B Fire Workshop: Soil recovery after wildfire and salvage logging (presentations & field tour, 70 participants) April 22, 2009	(1) Completed (2) Completed (3) Completed
JFSP Annual Reports	2005, 2006, 2007, 2008	Completed

IX. Literature Cited

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X. Additional Reporting

Note: This is a complete list of our presentations, papers, and other reports – both completed and in progress. Numbers in parentheses at the end of citations refer to the JFSP reference number available at www.firescience.gov).

Final Report

Smith JE, Sulzman E, Jennings TN, Hebel CL, McKay D, Shaw D. 2009. Impacts of Post-Fire Salvage Logging and Wildfire Burn Intensity on Soil Productivity and Forest Recovery, Final Project Report (JFSP Project Number: 05-2-1-44), June 1, 2009, Corvallis, OR. (1921)

Knowledge Transfer Workshops & Field Tours

Smith JE, Jennings TN, Hebel CL, McKay D, Shank D, Tandy B, Adams PW. 2009. *B&B Fire Workshop – Soil recovery after wildfire and salvage logging.* Knowledge Transfer Workshop and Field Tour. April 22, 2009. Sisters, OR. (8042)

About 70 participants attended this workshop and field tour. Study findings were presented in the morning session, followed by an afternoon of discussion in the field. A wrap up discussion of future research directions concluded the workshop. Presenters included PNW scientists and technicians, OSU College of Forestry students and professors, and Forest Service land managers. Attendees were resource managers from the Forest Service and BLM, Oregon State University professors and students, the timber industry, employees or members of The Nature Conservancy and the Sierra Club, and the general public.

Professional Presentations and Invited Talks

Jennings T, McKay D, Smith J, Hebel C. Life in red soils: investigating forest recovery after wildfire. NW Scientific Association, March 24-25, 2005, Corvallis OR – *Poster presentation* (3836)

McKay D, Jennings T, Smith J. 2005. *Investigating life in red soils.* Mycological Society of America, July 30 – August 4, 2005, Hilo, HI – *Poster presentation* (3838)

Smith JE. 2006. *Fuels, fire, and fungi.* North American Truffling Society meeting. Corvallis, OR. April 4, 2006. – *Oral presentation* (8039)

Hebel C, Smith JE. 2006. *Interactions between soil microbial communities and native and non-native plant species after wildfire in the Cascade Range of Oregon.* Subsurface Bioshpere Initiative Workshop/IGERT Retreat, June 18-21, 2006, Newport, OR – *Poster presentation* (3844)

Smith JE, McKay D. 2006. *Effects of prescribed fire and wildfire on fungal communities in ponderosa pine forests in eastern and central Oregon, USA.* July 23-26, 2006. Granada, Spain. – *Poster presentation* (3840)

Hebel C, Smith JE. 2006. *Interactions between arbuscular mycorrhizal fungi and native and non-native invasive plant species after wildfire in the Cascade Range of Oregon,* USA. International Conference on Mycorrhizas. July 23-26, 2006. Granada, Spain. – *Poster presentation* (3842)

Hebel C, Smith JE. 2006. *Post-fire microbial interactions with native and non-native invasive plant species east of the Cascade Range, Oregon.* 3rd International Fire Ecology & Management Congress. Nov. 13-17, 2006. San Diego, CA. UT – *Oral presentation* (6917)

Smith JE, McKay D. 2006. *Effects of seasonal prescribed fire and fuel reduction treatments on the ectomycorrhizal fungal community in ponderosa pine forests.* 3rd International Fire Ecology & Management Congress. Nov. 13-17, 2006. San Diego, CA. – *Poster presentation* (8040)

McKay D, Smith JE. 2006. *Life in red soils: Investigating soil fungi recovery during the first two years after wildfire.* 3rd International Fire Ecology & Management Congress. Nov. 13-17, 2006. San Diego, CA. – *Poster presentation* (6924)

Smith JE. 2007. *Ground Control: a belowground perspective of forests after fire.* OSU Forest Science Dept. Seminar. Feb. 8, 2007. Corvallis, OR. – *Oral presentation* (6918)

Smith JE, Mckay D, Beldin S, Jennings TN, Hebel CL, Sulzman EW. 2007. *Soil fungal recovery in severely burned soil two years after a stand replacing wildfire in central Oregon.* Soil Ecology Society meeting, April 29 – May 2, 2007. Moab, UT – *Oral presentation* (6922)

Jennings TN, Smith JE, Sulzman EW, Beldin S. 2007. *Impacts of post-fire salvage logging on soil bacteria species richness.* Soil Ecology Society meeting, April 29 – May 2, 2007. Moab, UT – *Poster presentation* (6923)

Smith JE, Mckay D, Jennings TN, Hebel CL, Beldin S, Sulzman EW. 2007. *Soil fungal recovery in severely burned soil.* Mycorrhizal Fungi symposium, May 10 – 13, 2007. Selma, OR – *Oral presentation* (6921)

Smith JE. 2007. *Influence of fire and forest restoration on soil fungal diversity.* International Symposium on Soil Biodiversity and Ecology, September 10-13, 2007, Taipei, Taiwan. – *Oral presentation* (6919)

Woolley T, Smith JE. 2008. *Native plant restoration following wildfire and non-native plant invasion: Do aboveground-belowground feedbacks affect native plant growth?* March 7, 2008, Fire Discussion Group, Oregon State University, Corvallis, OR. – *Oral presentation* (8041)

Jennings TN, Smith JE, Sulzman EW, Beldin S. 2008. *Impacts of post-fire salvage logging on soil bacteria in mixed conifer forests in Central Oregon.* Ecological Society of America, August 3-8, 2008, Midwest Airlines Center, Milwaukee, WI. – *Oral presentation* (7717)

McKay D, Smith, JE. 2008. *Investigating soil fungal recovery during the first two years after wildfire.* Mycological Society of America, August 10-13, Pennsylvania State University, University Park, PA. – *Oral presentation* (7718)

Hebel CL, Smith JE*, Cromack K, Jr. 2008. *Invasive plant species and soil microbial response to wildfire burn severity in the Cascade Range of Oregon.* Mycological Society of America, August 10-13, Pennsylvania State University, University Park, PA. – *Oral presentation* (7720)

Smith JE, McKay D, Hebel CL, Jennings TN. 2008. *Soil recovery after wildfire and salvage logging. Pacific Northwest Research Station, Science Summit,* October 29-31, Hood River, OR. – *Poster presentation* (8043)

Smith JE, McKay D, Hebel CL. 2008. *Soil recovery two years after a high severity wildfire in the Cascade Range of Oregon.* Pacific Coast Fire Conference: Changing Fire Regimes, Goals and Ecosystems, December 1-4, San Diego, CA. – *Oral presentation* (8044)

Smith JE. 2009. *The "hot" dirt on soil – recovery of forest soils after fire.* Seminar presented to the Department of Natural Resources and Environmental Sciences, University of Illinois at Urbana-Champaign. February 4, 2009, Urbana IL. – *Oral presentation* (8045)

Smith JE. 2009. *Investigating soil recovery after severe wildfire.* Seminar presented to the Oregon Mycological Society. World Forestry Center. April 27, 2009, Portland, OR. (approx. 70 attended) – *Oral presentation* (8046)

Education Outreach

McKay D. 2004. *What lives in a forest- with emphasis on forest fungi.* Presentations to grades K-4, 300 kids, Liberty School, Albany, OR. April 2004

McKay D. 2004. Forestry Tour 6th grade *Fungi in our forests including current research.* Clatsop County Extension, 250 kids, October 2004

McKay D. 2005. Forestry Tour 6th grade *Fungi in our forests including current research*. Clatsop County Extension, 250 kids, October 2005

McKay D. 2006. Forestry Tour 6th grade *Fungi in our forests including current research*. Clatsop County Extension, 250 kids, October 2006

McKay D. 2009. "What lives in a forest- with emphasis on careers and forest fungi" presentations to 5th grade, 65 kids, Liberty School, Albany, OR May 2009

Graduate Education

Hebel, Cassie L. 2007. *Effects of wildfire burn severity on soil microbial communities and invasive plant species in the Cascade Range of Oregon.* M.S. Thesis, Dept. of Forest Science, Oregon State University, Corvallis, OR (Jane E. Smith, advisor) (6916)

Jennings, Tara N. 2008. *Impacts of post-fire salvage logging on soil chemistry, physical properties, and bacterial community composition in a mixed-conifer forest in central Oregon.* M.S. Thesis, Dept. of Forest Science, Oregon State University, Corvallis, OR (Jane E. Smith, advisor) (7859)

Publications

Hebel C, Smith JE. 2006. Post-fire microbial interactions with native and non-native invasive plant species east of the Cascade Range, Oregon. Proceedings of the 3rd International Fire Ecology & Management Congress. Nov. 13-17, 2006. San Diego, CA. (8047)

Hebel CL, Smith JE, Cromack K, Jr. 2009. Invasive plant species and soil microbial response to wildfire burn severity in the Cascade Range, Oregon. Journal of Applied Soil Ecology, 42: 150-159. (7714)

Trappe JM, Molina R, Luoma DL, Cázares E, Pilz D, Smith JE, Castellano MA, Miller SL, Trappe MJ. 2009. Diversity, ecology, and conservation of truffle fungi in forests of the Pacific Northwest. Gen. Tech. Rep. PNW-GTR-772. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. (7716)

Deliverables in Preparation

Jennings TN, Smith JE, Sulzman E, Cromack Jr. K, Caldwell B. (manuscript in review). Impacts of post-fire salvage logging on soil chemistry, physical properties, and bacterial community composition in a mixed-conifer forest in central Oregon. *Forest Ecology and Management.*

Smith JE, McKay D, Hebel CL. Soil recovery two years after a high severity wildfire in the Cascade Range of Oregon.

Smith JE & others. Impacts of post-fire salvage logging on soil fungal community structure.

Smith JE & others. Effects of fire severity on soil fungi and bacteria

Smith JE & others. Effects of post-fire salvage logging and wildfire burn severity on the mycorrhizal community and growth of ponderosa pine and Douglas-fir seedlings.