Wildfire Effects on Vegetation and Soils at the Purdy Fire Site, Gallatin National Forest


Photo by Sara Zimmerley

Montana State University, LRES Capstone Course, Fall 2002

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Introduction

Wildland fire is a necessary process for sustaining a healthy and dynamic ecosystem. However, due to the expansion of human settlements into wildland areas of the western United States, fire suppression has become a necessary forest management tool. Fire suppression results in an increase in understory fuels, which combined with recent climatic conditions, have triggered extreme wildfire seasons. Pre-fire conditions play a key role in the effects of wildfires. Fuel load can influence burn intensity and, in turn, the degree of soil heating (Hungerford et al. 1990).

Fire effects on soils and subsequent site productivity are related to both the primary effects of combustion and soil heating, and secondary effects of post-fire erosion. The degree of organic matter combustion has a two-fold effect on the post-fire ecosystem, and may be the primary variable in determining post-fire effects across a landscape. Many effects on soil physical, chemical, and biological properties are related to the amount of organic matter (OM) consumed and temperatures reached within the soil. The incineration of the organic layer is directly related to increases in mineral nitrogen, available phosphorous, and other macro- and micronutrients (Hungerford et al. 1990).

Soil nitrate levels in burned soils are of key interest due to their biological importance for plant growth and microbial activity. Rapid mineralization of organic matter during combustion typically results in an increase in plant-available nitrogen (Raison 1979), however with increasing temperatures, nutrients can also be lost through volatilization (Blank et al. 1998). Plant and microbial uptake, surface erosion, and leaching of water-soluble nutrients typically reduce nitrate levels to pre-burn conditions within one year of the burn (Andreu et al. 1996).

Fire effects on vegetation depend on fire intensity (the amount of heat energy produced by a fire), the season of burning, and vegetation type (Hungerford et al. 1990). While certain forest species depend on fire for regeneration, the revegetation potential of other species depends on the maximum temperatures reached within the soil profile during a fire, which affects both established roots and the soil seed bank. The seed bank includes viable, ungerminated seeds stored either in the surface litter layer or within the mineral soil. Damage to the seed bank as well as the extensive loss of aboveground biota may be detrimental to system recovery following a fire.

Soil moisture content and the duration of the fire influence post-fire system responses. Although a natural property in some soils, a hydrophobic (water-repellent) layer is a common result of wildfire. Organic matter accumulates on the soil surface between fire intervals, and in many systems this natural organic matter accumulation and decomposition can produce a naturally hydrophobic layer below the litter layer. During a fire, the combination of combustion and heat transfer produces steep temperature gradients in soil layers, which can result in the formation of hydrophobic soil layers (DeBano 2000). Development of post-fire management strategies must address the presence or absence of a hydrophobic layer, because of the direct relationship between hydrophobicity and post-fire ecosystem responses, such as vegetation establishment and the degree of soil erosion.

Many factors determine how the environment will react to disturbance: fire-severity, nutrient availability, both native and non-native species colonization, and land management intervention. To study the effects of wildfire on soils and vegetation, the LRES Capstone course focused on a nearby wildfire site on and adjacent to Gallatin National Forest lands. The Purdy Creek fire burned from Sept. 26th through October 4th, 2001, burning just over 5000 acres approximately 20 miles south of Bozeman, Montana. On September 27th, 2001 the fire burned over 3000 acres. The Forest Service attributed this fire to three years of drought, high winds, and a lightning ignition. This site is of particular ecological importance due to the rare and pure population of Westslope Cutthroat Trout that inhabit Wilson Creek, which runs through the area. The vegetation is predominately lodgepole pine (*Pinus contorta*) forest with patchy grassland understory composed of huckleberry (*Vaccinium* sp.), twinflower (*Linnaea borealis*), and pinegrass (*Calamagrostis rubescens*). The soils in the area are Typic Cryochrepts.

Our study has three main objectives:

1. To measure wildfire effects on soil and vegetation one-year post burn.
2. To test the effects of burned soil on seed germination, plant establishment, and plant growth.
3. To measure soil temperatures across a soil profile with contrasting burn types, in the laboratory.

We selected two field sites within the Purdy Creek Fire area: Wilson and Cabin. The Wilson site is located just above the West Fork of Wilson Creek and has a cobbly loam soil. The

Cabin site is located adjacent to the Little Bear Gallatin National Forest Service cabin and has a cobbly sandy loam soil.

Figure 1. Severely burned site

Figure 2. Moderately burned site

When discussing wildfire, the terms severity and intensity are often used with varying definitions. We defined intensity as the amount of heat energy produced by a fire, and severity as the degree of effects of fire on ecosystem properties. Fire intensity measurements were not within the scope of this project.

Each site was divided into 3 categories of burn severity: severe, moderate and unburned. The severely burned sites had 100% tree mortality, no needles, lichens, or mosses on trees, and no remaining vegetative ground cover (Figure1). Moderately burned areas also had trees killed by fire, but some needles, mosses and lichens remained, and there was some remaining vegetative ground cover (Figure 2).

Field data was collected during the last week of August 2002, at the Purdy fire site. At both the Cabin and Wilson sites, we laid a 100-m transect across each of the three burn types. Ten quadrats, 1 m by ½ m, were randomly placed along each transect. Plant and soil data was collected from within each of the quadrats. Parameters measured include soil and vegetation characteristics and ground cover. Soil samples were also taken from just outside three quadrats on each transect for soil nutrient testing and plant growth studies.

Field Data

Field Data Methods

Soil characteristics measured included evidence of erosion (rill formation), hydrophobicity, and depth to the hydrophobic layer. Erosion was measured by the visual appearance of rill formation. Hydrophobicity was calculated by water infiltration rates, with infiltration time greater than 5 seconds indicating a hydrophobic layer. Ground cover was measured by visually estimating the percent of vegetation, rock, and bare ground within a quadrat. Cover classes were categorized into six classes: 0 = none, 1= trace (0-1%), 2 = 1-10%, 3 = 11-25%, 4 = 26-50%, 5 = 50-100%. The depth of the litter layer, or surface organic matter, was measured at five points within each quadrat, and average surface organic matter depth was calculated for each quadrat. All plant species within each quadrat were identified and stem densities counted. Diversity was measured using the Simpson's Diversity Index, which incorporates both species richness (the number of species present) and their evenness of distribution. Simpson's Diversity Index was calculated using the following formula:

$$D = \frac{1}{p_i^2}$$

where p is the proportional density of each species present, calculated as the stem density of each species divided by the total stem density of the quadrat. The field data is presented in box and whisker plots (Figures 3-6), which describe the variance found within the data. The box within the graph contains 50% of the data, and the bar within the box represents the median value of the data set. Whiskers are the minimum and maximum values excluding the outliers, which are indicated as symbols in each chart.

Field Data Results and Discussion

Rill formation was present in all of the moderately burned quadrats and 100% of the moderately burned quadrats at the Wilson site. The unburned Wilson site was level and thickly vegetated with a dense surface organic matter, and no rill formation was documented. At the

Cabin site, 20% of the unburned quadrats and 90% of both the moderate and severely burned quadrats had either slight or moderate rill formation.

Hydrophobicity was measured because of its link to erosion. Hydrophobic layers are water-repellent layers of variable thickness and spatial continuity that are sometimes present after a fire. This layer forms when heat produced by the burning of surface organic matter volatilizes organic substances, which then move downward into the soil until they reach cooler soil layers, causing them to condense. Fire temperature and duration along with soil properties such as texture, water content, amount of OM, and the soil-plant environment all affect the extent of hydrophobic formation (DeBano et al. 1976). For all but the unburned Wilson quadrats, hydrophobicity was present and showed a high amount of variance with severity within each site (Figure 3). The unburned transect in the Wilson site is represented by an outlier, because soils along the transect were saturated, precluding possible measurements in all but one sample. Because hydrophobicity was present in the Cabin unburned soils, along with all moderately and severely burned soils, it is not possible to differentiate whether hydrophobicity is naturally occurring or induced by fire.

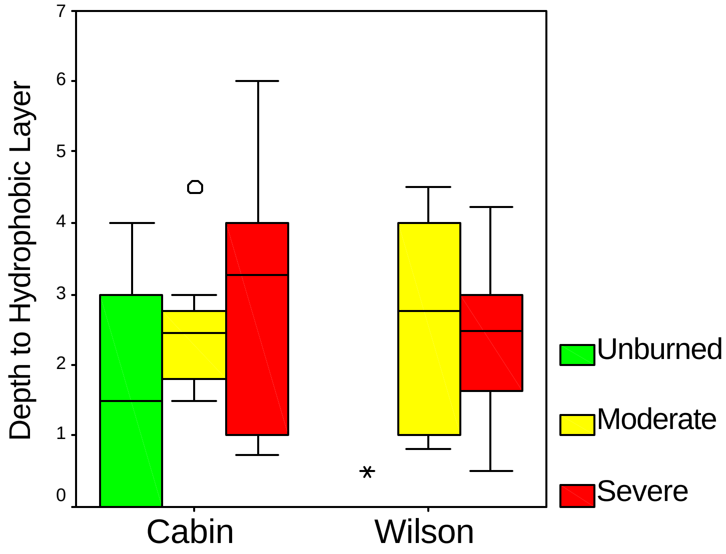
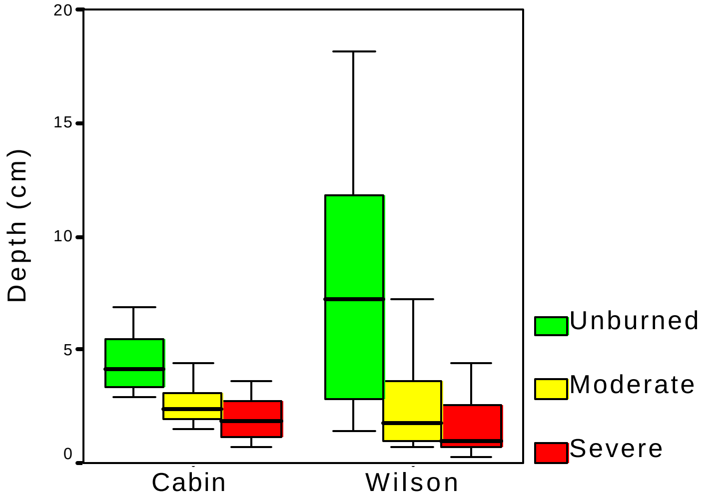


Figure 3. Depth of Hydrophobic Layer



Surface organic matter, the litter layer on top of the mineral soil horizons, was measured because of its important role in the ecosystem. The litter layer regulates soil microclimates. It serves as a large storage area of nutrients and viable seeds, and reduces erosion thereby protecting valuable soil resources. Surface organic matter was much higher in the unburned sites than in either moderately or severely burned sites (Figure 4).

The unburned transect in the Cabin site represents the variability found in the depth of surface organic matter in the field. Vegetation cover was greater in the unburned than the burned areas for both sites (Figure 5). The unburned Cabin site had a median cover of 76%, while the unburned Wilson area had a 70% median cover.

In the moderately burned Cabin site there was a decrease in cover to four percent, while the moderately burned Wilson, severe Wilson and severe Cabin sites all have a median of cover of zero percent with only a few sample points having a value greater then zero. All sampled data excluding the outliers lay upon the median bar. Low vegetation cover is a concern because this reduction increases susceptibility to erosion.

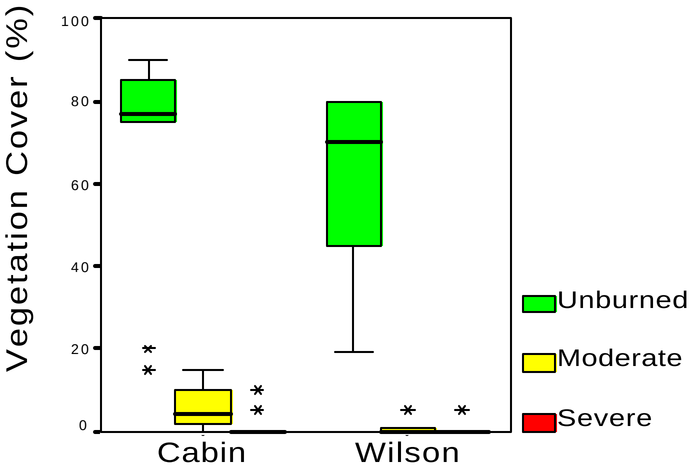


Figure 5: Vegetation cover

The species that were present in the burned areas are represented in Table 1. *Arnica diversifolia* was the only species present in all four burned areas, *Carex* was found only in a moderately burned area, and a *Vaccinium* species was present in three of the burned areas.

Moderate	**Severe**
Wilson	**Wilson**
Winter wheat	Winter wheat
Arnica diversifolia	*Arnica diversifolia*
Vaccinium scoparium (grouse whortleberry)	*Vaccinium membranaceum* (mountain huckleberry)
Cabin	**Cabin**
Carex spp. (sedge)	*Epilobium angustifolium* (fireweed)
Arnica diversifolia	*Arnica diversifolia*
Vaccinium scoparium (grouse whortleberry)	*Spirea betulifolia* (birch-leaved spirea)

Table 1. Species with highest percent cover in burned areas

All the species listed had less than 1% cover in the burned areas excluding *Carex*, which had only 1.6 % cover. To reduce post-fire erosion, winter wheat was aerially seeded at the Wilson site, however cover by winter wheat was also less than 1% in all quadrats.

Species richness was greater in the unburned than the burned areas, with little difference between the moderate and severely burned areas (Figure 6a). Species diversity (which incorporates richness and evenness) was significantly greater in the unburned area than in burned areas, with again no difference between the moderate and severely burned (Figure 6b).

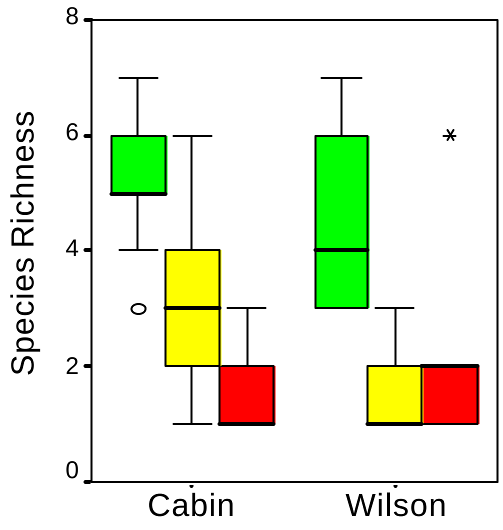


Figure 6a. Species richness

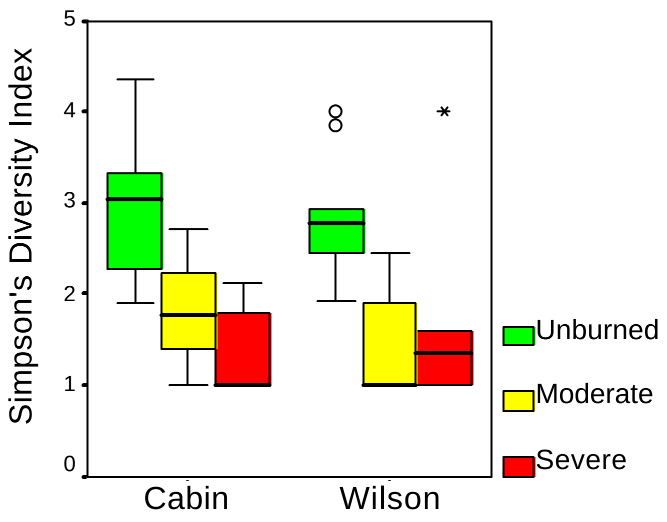


Figure 6b. Species diversity

Soil Chemical Analysis

Although studies agree that the soil matrix is affected by increasing fire intensities, the amount of alteration is highly variable and relatively short-lived. The chemical and physical changes induced by fire have immediate and long-term effects on the surrounding ecosystems. Using literature reviewed we formulated hypotheses for seven soil parameters, sampled one year post fire. The parameters are pH, electrical conductivity (EC), organic matter (OM), ammonium (NH_4^+), nitrate (NO_3^-), phosphorus (P), and potassium (K^+). We hypothesized that the concentration of NH_4^+, P, and K would be higher in the moderately and severely burned transects, as compared to the unburned, and that pH and EC levels would increase. In addition, we hypothesized that concentrations of NO_3^- and percent OM would decrease as burn severity increases.

Methods

We tested soils at two depths, which were determined in the field by sampling the top affected soil and taking an equal amount of unaffected soil as the bottom layer. Tests for pH and EC were done using a 2:1 water to soil ratio. Soil organic matter was calculated by the Walkley-Black method. Ammonium and NO_3^- were analyzed with a Lachat colorimeter and a 5:1 Calcium hydroxide dilution. The Bray-P method was used for determining concentrations of ortho-phosphate. Potassium was extracted with ammonium acetate and analyzed by atomic absorption.

Results-Discussion

Soil parameters measured in this study varied significantly between sites for pH and P (Table 2). All parameters except pH and NO_3^- were significantly different with increased fire severity, while only pH, EC, NH_4^+, and K varied with depth (Table 2).

	Site	Severity	Depth
pH	X		X
EC		X	X
OM		X	
NH_4^+		X	X
NO_3^-			
P	X	X	
K		X	X

(Each X indicates a statistically significant effect measured with ANOVA at a p value of 0.10)

Table 2. Significant parameters

Soil pH levels varied significantly between sites, averaging 5.6 at the Cabin site and 5.1 at the Wilson site. This variation is due to specific site dependent variables. Soil pH also showed a change between top (5.77) and bottom (5.21) layers of the moderate and severe burned transects. This increase was probably due to heat induced hydroxide formation and volatilization of organic acids. Electrical conductivity varied significantly for both severity and depth, but concentrations were biologically insignificant ranging from (0.178-.060 dS/m) averaged across site, severity and depth.

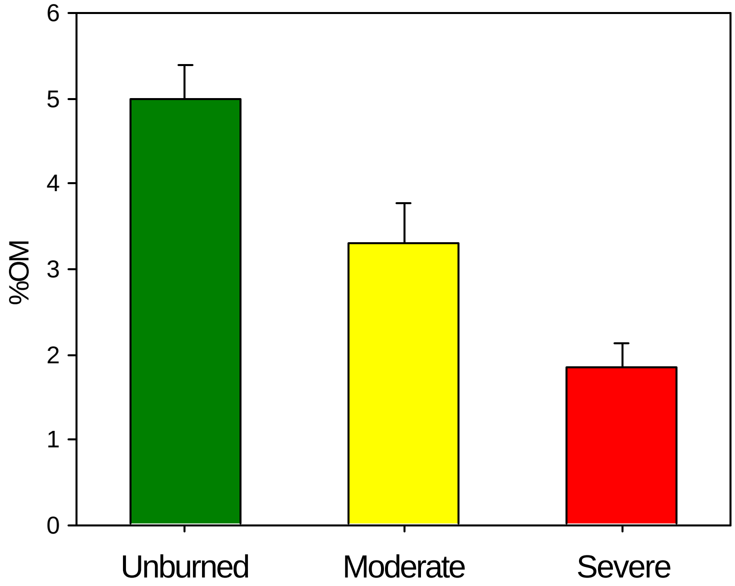


Figure 7. OM vs. Severity

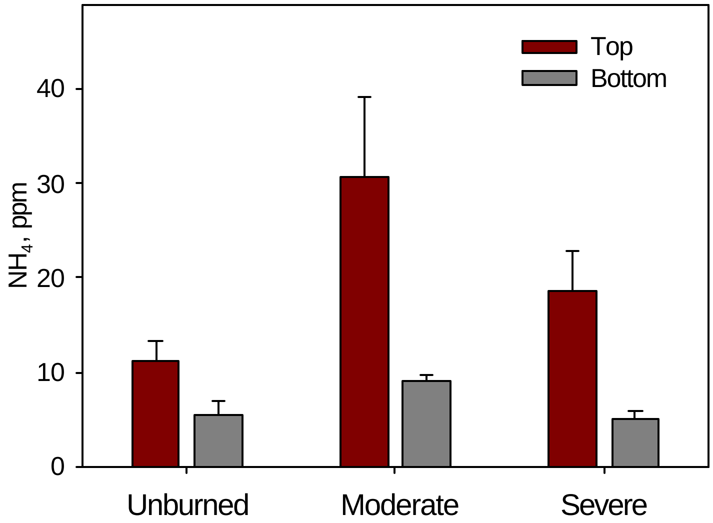


Figure 8. NH_4^+ concentrations by severity and depth

As hypothesized there was a linear decrease in percent soil OM with an increase in burn severity (Figure 1). Organic matter decreased due to combustion and volatilization as well as the removal of ash by wind and water erosion.

Consistent with Choromanska and Deluca (2001), we observed an increase in NH_4^+ concentrations in burned soils relative to unburned soils. The trend across severity is the same for both top and bottom layer, but the magnitude of the change is greater in the top. There was a three-fold increase from the unburned to the moderate quadrats, probably due to scorching or partial combustion of vegetation, releasing immobilized ammonium with limited volatilization. Ammonium levels in the severely burned soils were lower than in the moderately burned soils because of more complete combustion and volatilization, as well as losses associated with ash movement. In contrast to NH_4^+, our NO_3^- data was inconclusive. Consistent with the results of Andreu et al.

(1996), we expected an increase in nitrate levels after a fire, but concentrations, even in the unburned soils, were below detectable limits.

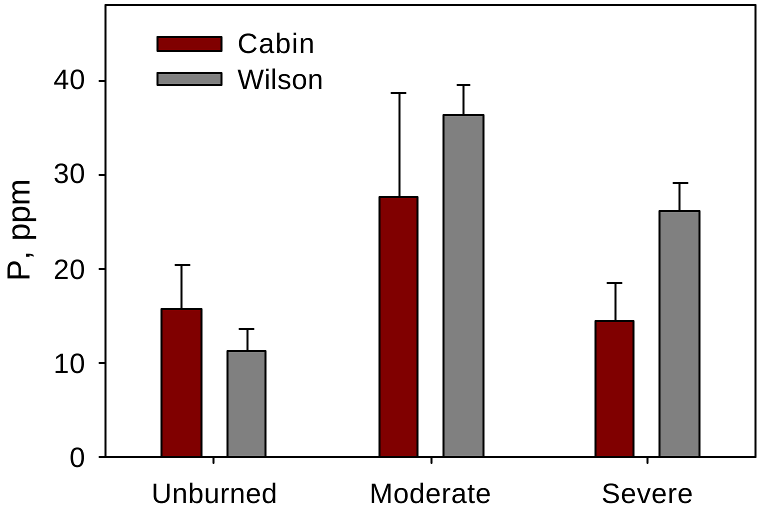


Figure 9. Soil P vs. site and severity

Concentrations of P were lowest in the unburned soils (Figure 9) since it was not found in forms extractable by the Bray-P method. Phosphorus concentrations were highest in the moderate transects probably because the surface OM was only partially consumed, resulting in increased P in the ash layer. The levels decreased in severely burned soils possibly due to leaching through the soil profile and ash movement off-site.

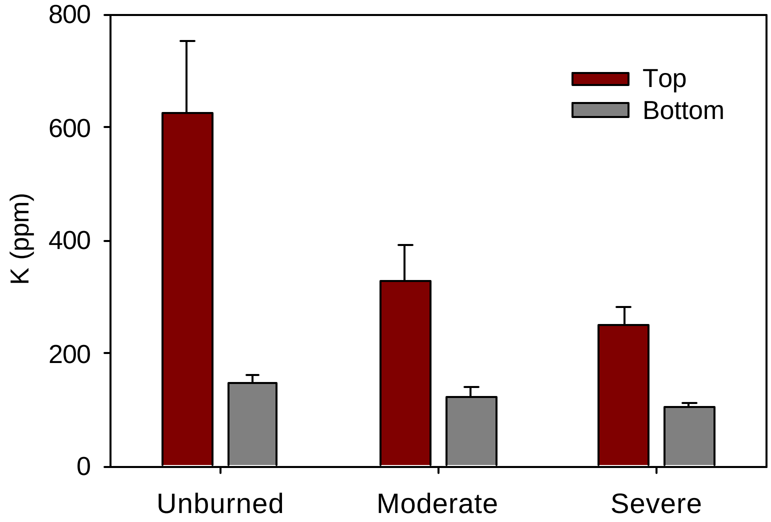


Figure 10. Soil K vs. severity and depth

Potassium levels were highest in the unburned transects, and decreased in moderately and severely burned soils (Figure 10). The dramatic decrease in burned soils was associated with the combustion of OM, making K vulnerable to leaching and erosion.

Conclusions

With an introduction of fire into these systems, nutrient rich organic material is consumed, producing a fertile ash layer. Burns of low to moderate intensity result in a partially combusted organic layer which is somewhat resistant to erosive processes, resulting in short term increases in soil nutrients. However, as severity increases, nutrient concentrations decrease due to the ensuing off-site movement of the ash. These chemical changes and subsequent increase in surface erosion will impact site quality and may have an effect on adjacent ecosystems.

Seed Bank

Revegetation potential is affected by the type and amount of soil nutrients present after a fire and the density of viable seeds and propagules (Baskin and Baskin 1998). The density and composition of the seeds present in the soil can be measured through either direct seed counts, after separating seeds from the soil, and identifying them to species or genus. Alternatively, the seedling emergence method entails identifying and counting seedlings that emerge from soil samples brought in to the greenhouse (Baskin and Baskin 1998). We used the latter method, and compiled data to test two hypotheses:

H1: Seed bank density and species richness will decrease as fire severity increases.

H2: Seed bank density and species richness will be greater in the litter layer than the A-horizon.

Materials and Methods

Soil samples from each of the burn types at both sites were collected in early July 2002. Twenty soil cores (5.6 cm diameter x 5.0 cm depth) were extracted from randomly located collection spots within each burn type, for a total of 120 samples. Soil samples were spread on potting soil in 18 cm diameter pots, placed in the greenhouse and kept moist to provide optimal conditions for seed germination. Six control pots containing just potting soil were included to determine whether there were seeds present in the potting soil. The pots were randomly arranged on the greenhouse bench and rotated weekly to minimize effects of environmental gradients within the greenhouse. Seedlings were counted weekly and identified.

To determine the seed distribution within the soil profile, we collected 5 soil samples, averaging 10 x 10 cm across and 7 cm deep, from unburned areas at the Cabin and Wilson sites. The litter layer was separated from the A-horizon, and samples were spread on potting soil in 30.5 x 30.5 x 7.5 cm pans. Two control pots containing commercial potting soil were also included in the study to verify that seeds were not present in the potting soil. Seedlings were counted weekly to determine the species richness and seed bank density for each horizon.

Results

The unburned areas at each site had the greatest average number of seeds, 850seeds/m^2. The moderately burned and severely burned sites had 160 seeds/m^2 and 50 seeds/m^2 respectively (Fig. 11). The number of seeds declined significantly as fire severity increased. Studies have shown that total seedling density is higher in heat-treated soil due to the fact that some species require a heat treatment to break dormancy (Izhaki et al. 2000, Wills and Read 2002). However, other studies have shown that seedling density decreases due to fire or heat (Odion and Davis 2000, Schimmel and Granstrom 1996).

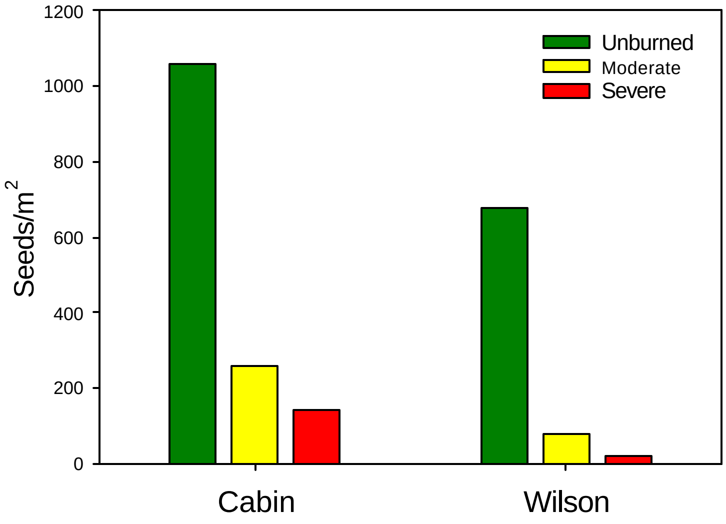


Figure 11. Seed density

There are several reasons for the disparity between these two groups of studies. Fire effects on a soil seed bank depend on the species present, the maximum temperature reached during the fire, the duration of the maximum temperature, the moisture content and heat tolerance of the seeds (Odion and Davis 2000), and the distribution of the seeds in a soil profile. Our study is consistent with results from Odion and Davis (2000) and Schimmel and Granstrom (1996), as we saw a decrease in seed density as fire severity increased.

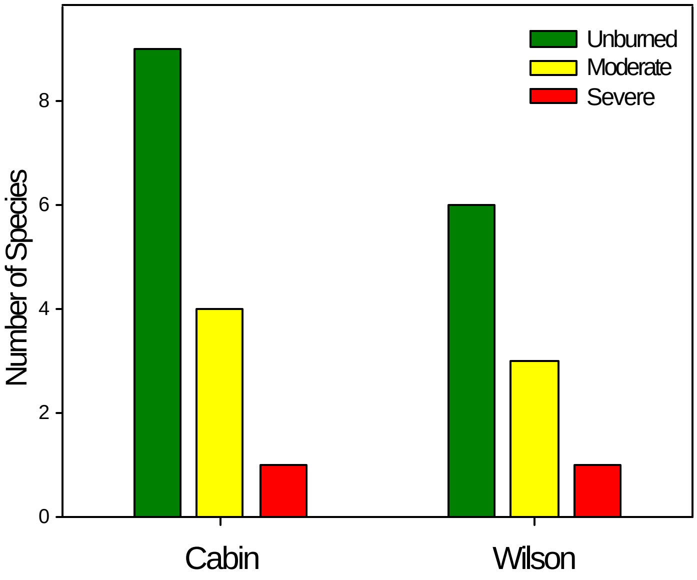


Figure 12. Seed bank species richness

Species richness of seeds stored in the seed bank declined as fire severity increased (Figure 12). Nine species were found in the unburned, Cabin site soils, while only one species, *Trifolium*, was found at both severely burned sites. Interestingly, *Trifolium* was only found in the severely burned pots, and it emerged sooner than any other species in the moderate and unburned pots.

Heat-treating soil results in an increase in species richness in some studies (Wills and Read 2000), but not others. For example, Izhaki et al. (2000) saw a decrease in species richness when samples were covered with ash. In our study, the decrease in species richness may be the result of increasing combustion of organic matter with increasing fire severity, with loss of the litter layer and the seeds contained within. Figures 11 and 12 support our first hypothesis, that seed density and species richness will decrease as fire severity increases.

To test our second hypothesis, we assessed seed distribution in the surface litter layer and the A horizon in the mineral soil. To survive a forest fire, seeds must either be able to withstand high temperatures or be buried deep enough to avoid high temperatures (Schimmel and Granstrom 1996). Table 3 shows the seed density in the litter layer and the A-horizon. From this table, it is clear that there are more seeds found in the litter layer than the A horizon with approximately 10 times as many seeds/meter^2 in the Cabin litter layer than the Cabin A horizon. Seed bank density in moderately burned soils should be equivalent to this number if the major impact on the soil is the loss of the litter layer. In severely burned soils however, seedbank density would be lower if the A horizon reaches a lethal temperature during burning. Our data supports our second hypothesis, which stated there would be a larger seed density in the litter layer than the A-horizon.

	Cabin	Wilson
Litter layer	3483	670
A horizon	360	450

Table 3. Seed distribution vs. soil horizon in seeds/m^2

The potential for the seed bank analysis to be directed toward understanding revegetation potential can be addressed by comparing our seed bank results to vegetation data from field transects. Some species were found only in field transects or only in the seed bank, but not both. This may be because of different germination conditions in the greenhouse versus the field, or due to the patchy distribution of seeds in the field, or that some species were poorly represented in the seed bank. In the field data, *Vaccinium* and *Spirea* were found in the moderately and severely burned sites, but not in our seed bank data. Based on the size of the plants in the field, it is very likely that these species are regenerating vegetatively from surviving root segments and not from seed. These species may be especially important for site response after fire, since the already well-established roots can provide immediate slope stabilization.

Epilobium and *Carex* species, which were among the most common species in the burned sites in the field, were found in the seed bank, but not in the moderately or severely burned soils. Additionally, no winter wheat or *Arnica* emerged in the seed bank study. This discrepancy between field revegetation patterns and our seed bank data could be due to the patchy distribution of both the fire and surviving seeds. A much larger sample size could help to elucidate patchily distributed species.

In conclusion, unburned sites had greater seed density and species richness than the moderately or severely burned sites. Additionally, more seeds are stored in the surface litter layer than in the soil A horizon. The decrease in seed density and species richness in burned areas may be due to the combustion of the litter layer in moderately burned sites. In the severely burned sites, both litter layer combustion and higher soil temperatures reaching lethal levels may explain our results. Seed bank data can provide information to managers on site revegetation potential post-fire, and species composition relating to invasive species and weed control issues.

Seed Germination and Plant Growth in Burned Soils

Understanding the effects of burned soils on seed germination, emergence, and plant growth can provide land managers with a better understanding of how the environment responds to fire and the ecological effects that determine plant regeneration. With this portion of the research we tested seed germination rates in aqueous extracts and in field-collected soil. We also measured plant growth in burned and unburned soils. Our overall objective was to determine whether burned soils affect plant establishment and growth. We compared both native and non-native species response.

Germination in aqueous extracts

Seed germination in aqueous extracts was compared using four plant species and soils from the three burn types at both the Cabin and Wilson sites. Two non-native species chosen for this experiment were spotted knapweed *(Centaurea maculosa*) and dalmation toadflax *(Linari dalmatica).* Spring wheat (*Triticum aestivum*) was tested because of its similarities to winter wheat, which was aerially seeded over portions of the Purdy fire site. Bluebunch wheatgrass (*Agropyron spicatum*), a species native to Montana, was also tested. A total of 96 germination boxes (2 sites with 3 burn types, four species, and 3 replications, plus one control for each species) were established.

Following the methods of Blank et al. (1998), seeds were soaked in aqueous extracts, and not in direct contact with soil. Aqueous extracts were prepared by oven-drying soil samples at 100°C. The samples were then ground and filtered through a 2mm sieve. A 1:10 soil-water solution was agitated for three hours using a magnetic mixing plate. Extracts were made by filtering the slurry twice through a 1.5µm pore glass microfiber filter. Twenty milliliters from each extract was placed into a germination box, containing 25 seeds that were evenly dispersed on blotter paper. Controls were created using de-ionized water in place of the soil extracts.

Germination boxes containing winter wheat seeds were placed into a germination chamber at a constant temperature of 20°C in total darkness. The other three species were placed in a separate chamber with artificial light for 15 hours per day, with temperatures ranging from 15 to 25°C. After the first four days, the seeds were checked every two days and germinated seeds were counted and discarded.

After two weeks, viability of all non-germinated seeds was tested by soaking the seeds in 2-3-5 triphenyl-tetrazolium chloride for approximately 12 hours. Seeds were dissected, and those with embryos that absorbed the stain were recorded as dormant.

Germination in soils

Seed germination was also tested in soils collected from the Purdy Fire site. Three species of plants were chosen for this study: bluebunch wheatgrass, milkvetch (*Astragalus cicer*), and spotted knapweed. According to the Forest Service, bluebunch wheatgrass and milkvetch were recommended as reseeding possibilities. Milkvetch was chosen because it is a nitrogen fixer, and because burn severity effects on nodule formation could be examined. Spotted knapweed was chosen because it is a non-native invasive species in western Montana.

At both the Cabin and Wilson sites, soils from each burn type were collected intact and placed in 13 x 13 x 14 cm pots. All existing plants in the soils were removed to eliminate effects of plant competition. One hundred seeds of a single species were scattered on the soil surface. Milkvetch seeds were first scarified using 1000 grit sandpaper to promote germination. The plants were watered daily and germination was counted twice weekly. The appearance of both cotyledons above the soil surface indicated dicot germination and a single leaf for the grasses indicated grass germination.

Plant growth

After 20 days, the pots were thinned to 3 plants to maximize the growth potential of the seedlings. Newly emerged plants were counted and removed throughout the remainder of the experiment. After 40 days, plants were harvested, oven-dried at 100 °C for 48 hours and weighed to determine above- and belowground biomass. All data were analyzed using ANOVA and significance was determined with a p-value of 0.05.

Results

Germination in aqueous extracts

Germination rates varied significantly between species, because seed size, volume-to-surface-area ratio, and hardness of seed coat affect germination rates (Gashaw 2002). At the Wilson site, spotted knapweed had highest germination rates in the severely burned soils, but decreased across the burn gradient (Fig. 13).

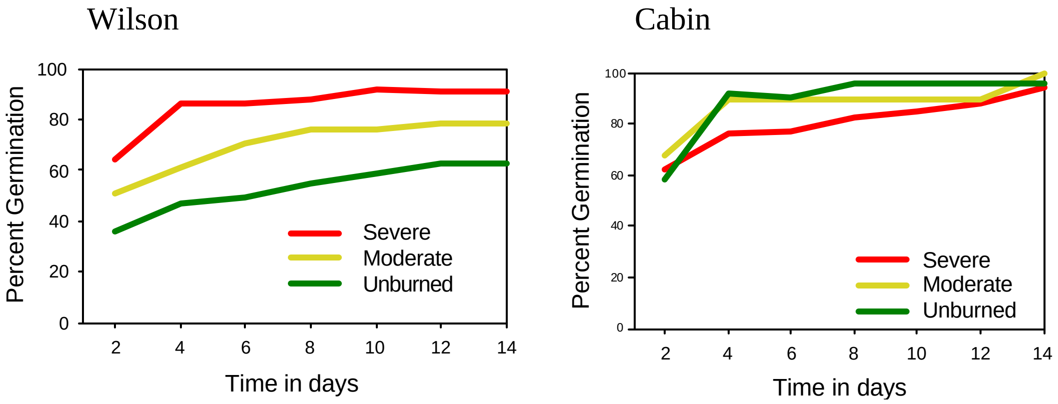


Figure 13. Percent germination of spotted knapweed

Dalmatian toadflax had increased germination at both sites in severely burned soil extracts (Fig. 14), but overall the germination rates were much lower for this species. Seeds were tested for viability and the majority of the seeds were dormant, suggesting delayed germination in dalmation toadflax.

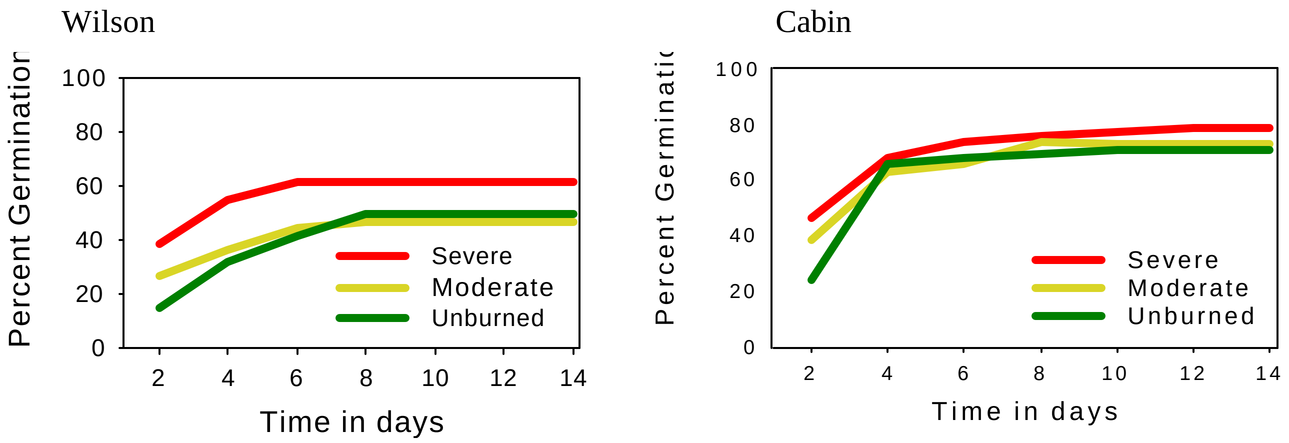


Figure 14. Percent germination of dalmation toadflax

Spring wheat germination was high at both sites and not significantly different in soil extracts between burn severities (Fig. 15).

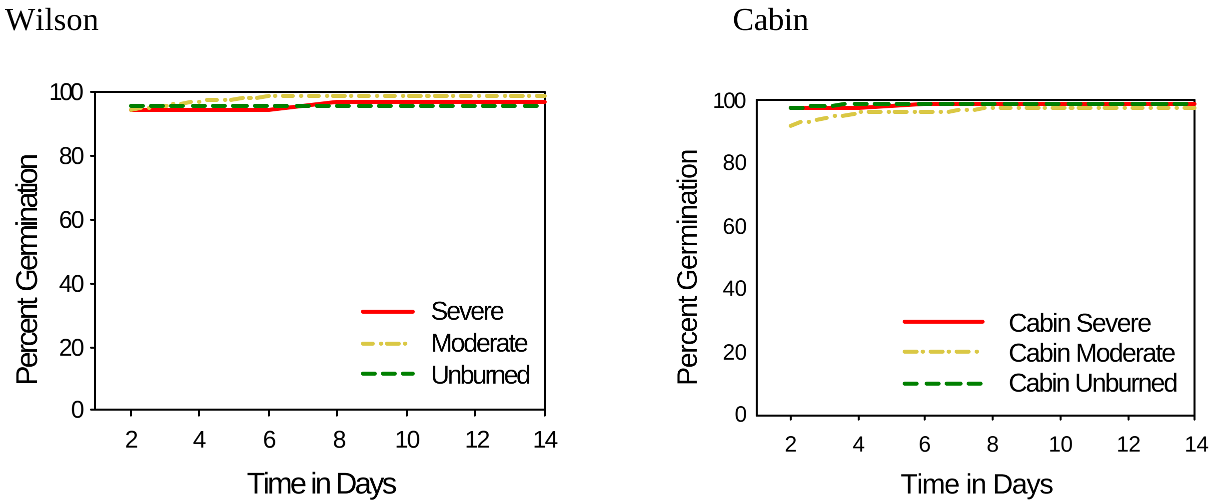


Figure 15. Percent germination of spring wheat

Bluebunch wheatgrass germination rates followed the same pattern as spring wheat, with the exception of a slower initial germination rate prior to day four. (Fig. 16).

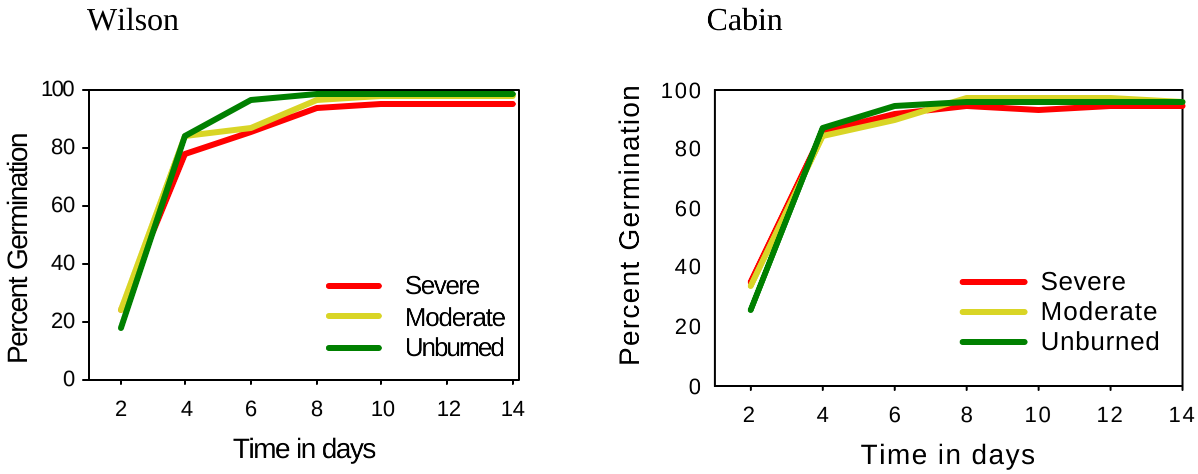


Figure 16. Percent germination of bluebunch in extracts

Germination in soils

Seed germination rates in soils varied significantly between sites, burn types, and species. Spotted knapweed germination rates were significantly higher at the Cabin site (Fig. 17). There was no significant difference in germination rates across the burn gradient. Germination rates were greater in the unburned and moderately burned soils from the Cabin Site. In contrast, the highest germination rates were in severely burned and unburned soils from the Wilson site.

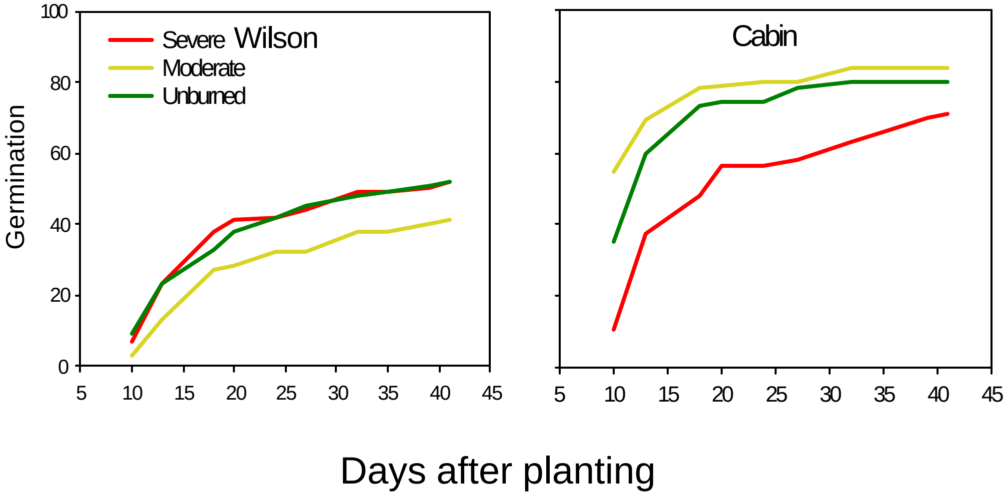


Figure 17. Knapweed percent germination in soils

Germination of bluebunch wheatgrass varied significantly between severities at both sites. Germination rates in moderately and severely burned soils were higher than in unburned soils (Fig. 18).

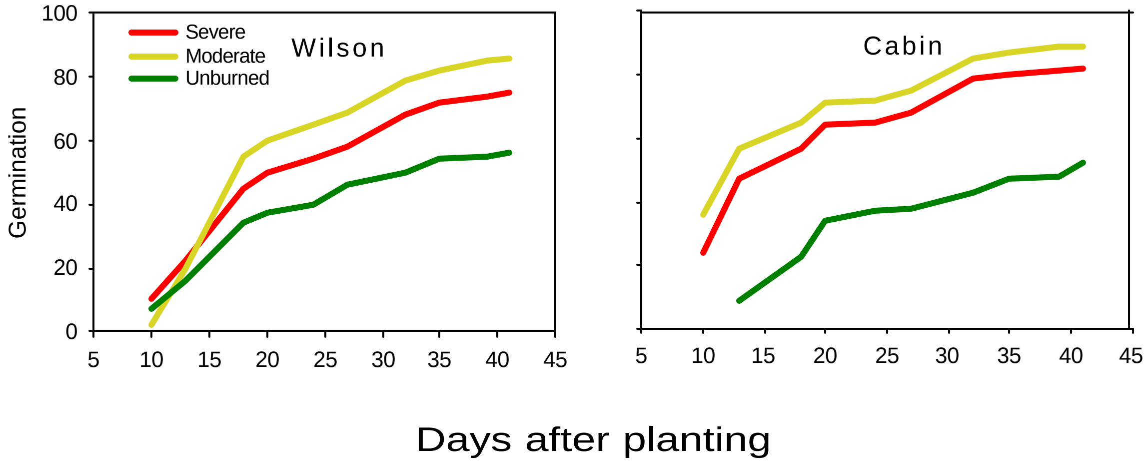


Figure 18. Bluebunch germination in soils

Milkvetch germination varied significantly among burn types and between sites. Germination rates in soils from the Cabin site were higher than in soils from the Wilson site (Fig 19). Between burn severities, seeds in Cabin soils had greater germination in severely burned soils, while germination was highest in the unburned soils at the Wilson site. There was a peak milkvetch germination after 34 days, the cause of which was not determined

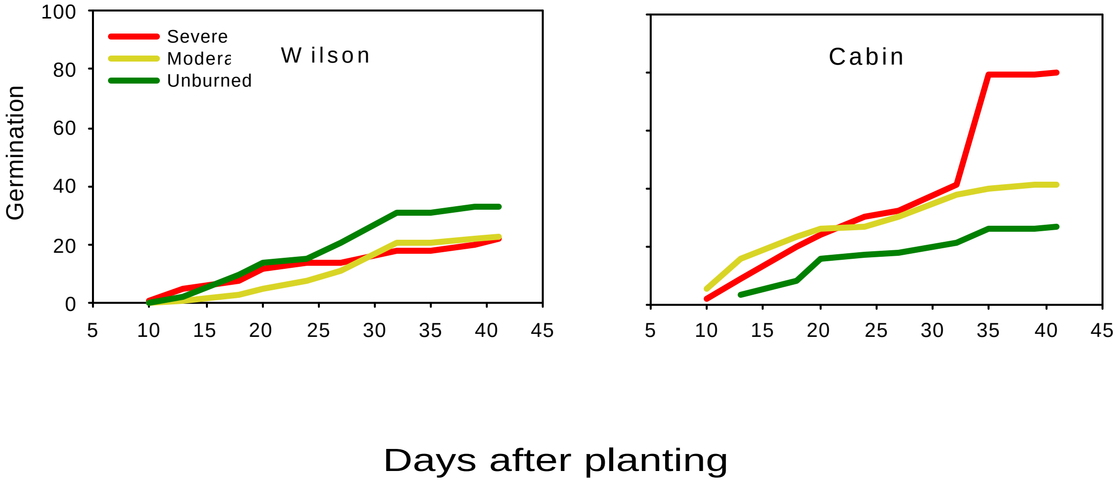


Figure 19. Milkvetch germination in soils

Biomass

Biomass of spotted knapweed varied significantly between burn intensities at both sites. Total biomass was greater at Wilson in the unburned soils and in the moderately burned soils at Cabin. However, the total biomass of both sites demonstrates an increasing (but not statistically significant) trend along the burn gradient (Fig. 20). The total biomass of bluebunch varied significantly with site and severity, and growth was higher in soils from severely burned soils (Fig. 20). Milkvetch total biomass varied significantly between severities and sites. The total biomass was greater at Wilson in unburned soils and at Cabin in severely burned soils. We saw no presence of nodule formation upon examination of the roots after harvesting. It is possible that nodules were not present because they can take up to three years to form.

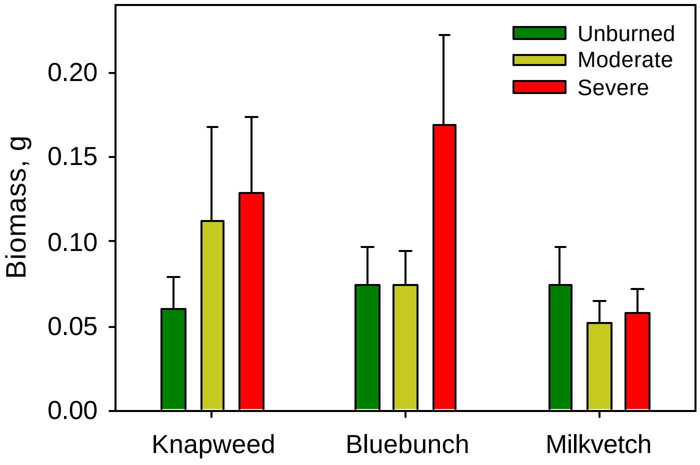


Figure 20. Biomass by species

Discussion

Germination is an important component of plant re-establishment, and both spatial and temporal variability in the environment have a large influence on germination cues. Rates of spotted knapweed germination in this study illustrate the effects of site heterogeneity on re-establishment. This species had increased germination rates in aqueous extracts with burn severities at the Wilson site, but germination was not affected by extracts from different burn severities at the Cabin site. The mechanisms resulting in changes of germination rates are unknown (Blank 1998, Keeley and Fotheringham 1998), but it has been hypothesized that extracts from burned soils may function by increasing the permeability of a seed coat or causing an enzymatic reaction, thereby initiating the germination process (Blank 1998).

In burned soils, bluebunch wheatgrass had significantly higher germination rates and greater biomass. This is consistent with Blair's (1997) research where greater biomass was found among grass species in burned areas. Jensen et al. (2001) supported this finding, concluding that increased fire intensity was more detrimental to broad-leaf plants than grasses. The results from our study and previous research would suggest bluebunch wheatgrass, a native species to Montana, would be a candidate for post-fire reseeding. Further research on its ability for re-growth in soils affected by fire would be beneficial for post-fire land management.

It is difficult to draw any conclusions about invasive species germination and growth in burned soils from this study. Fire severity effects on knapweed germination were not consistent between aqueous extracts and soils. For spotted knapweed, germination increased with burn severity in aqueous extracts at one site only, and there were no burn effects in germination in field soils. In comparison with bluebunch wheatgrass, spotted knapweed and dalmation toadflax had similar or lower germination rates. Dalmation toadflax germination rates increased along the burn gradient, although no biomass studies were conducted. To compare invasiveness of non-natives species in soils affected by fire, more research is needed.

The intensity of the fires and what seeds persist in the seed bank will determine what plants will grow to stabilize the ground surface. Reseeding and the invasion of non-native species are other factors that can hinder the regeneration of native species. It is important to look at each site specifically to determine what risks may affect the regeneration of the native plants and to what degree the soils have been damaged. To accomplish this, managers must research and monitor affected areas appropriately.

Laboratory-burned soils

With this component of our research, we designed a procedure to simulate wildfire heating by an open flame with an intact unburned soil profile taken from the Purdy site. We examined fire effects on soil temperature with depth and time, heat transfer through a profile in both cool and hot burns, and dry and wet treatments, and used a computer fire simulation model (FOFEM) to examine a number of fire-soil interactions. We also investigated the development of a hydrophobic soil layer.

Materials and Methods

Several trial experiments were conducted to create the most effective design. The final design (Figure 21) was a 30 x 30cm metal pipe capped with a PVC base, with 1/2cm vent holes for aeration near the surface, and ¼ cm thermocouple holes at 0, 2 and 5 cm depths, measured from the soil surface. We attached 178cm of 2mm-thick thermocouple wires to a Campbell Scientific CR23X microdatalogger, which was programmed to record data at 10-second intervals. Thin metal pins were used to pre-penetrate the soil profile before thermocouples were inserted, so as to avoid damage to the wires. Two thermocouples on opposite sides of the soil profile were inserted at each depth.

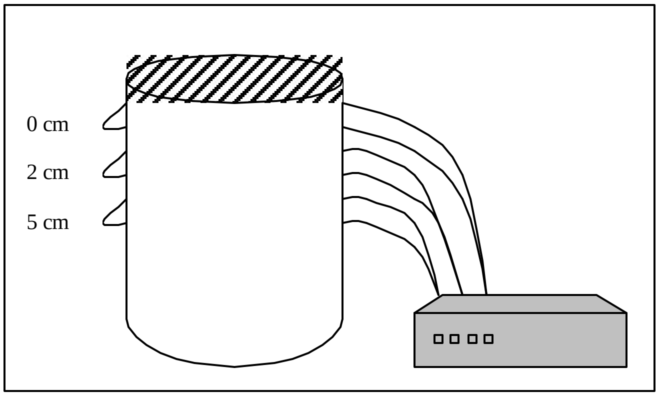


Figure 21. Design of soil profile with attached thermocouples

Four burning treatments were conducted by varying fuel load and moisture content: hot dry, hot wet, cool dry, and cool wet conditions. Soil burn components were oven-dried at 125°C for varying lengths of time: 24hrs for commercial peat and duff collected from the field; 72 hours for the mineral soil; and 120 hours for the topsoil. The soil profile used for the burn treatments consisted of, from top to bottom: 1cm commercial peat, 2cm of duff collected from the field (predominantly lodgepole pine needles), an intact topsoil layer from the field, and mineral subsoil from the field (Figure 22). The hot treatment consisted of the same order and amount of components listed, with the exception of a of a pre-ignited wood fuel source placed on the

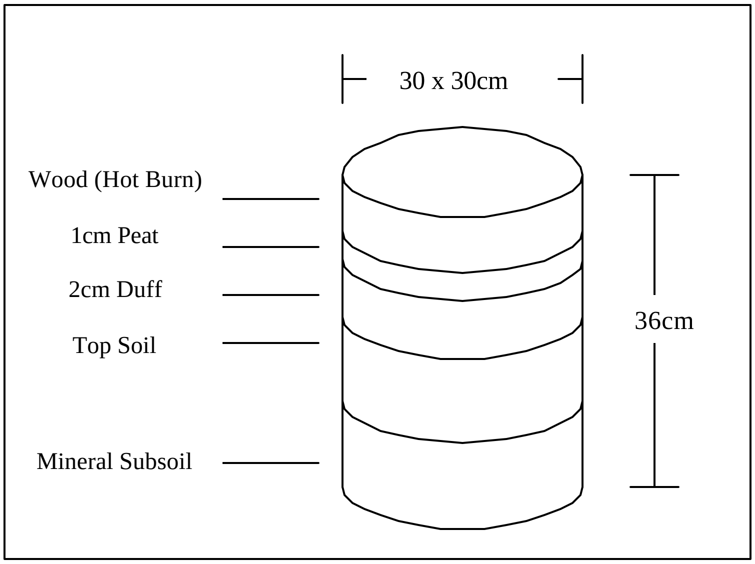


Figure 22. Components for hot and cool conditions

surface. For the wet treatment, water was added to oven-dried soil to 15% volume by mass. The sample was soaked in a plastic bag for 48 hours. The amount of water added and adsorbed into the sample was representative of field capacity conditions.

Burn trials were conducted outside with two columns at a time, so that hot and cool treatments could be burned simultaneously. Approximately 5mL of ethylene alcohol was added to the peat layer for the cool burns. For the hot burns, a comparable amount of ethylene alcohol was applied to kindling, which was placed on top of the peat once it reached a burning coal state. For all treatments, fires burned for 25 minutes after which they were immediately extinguished with minimal amounts of water and covered with aluminum and plastic wrapping to reduce the oxygen supply.

Hydrophobicity was visually measured after the samples were relatively cool. Water droplets were applied at 2cm intervals from the surface to a 10 cm depth. If the water droplet did not infiltrate the soil after 5 seconds, the layer was classified as hydrophobic.

Temperature Distribution with Depth

As expected, temperatures at the soil surface during the hot burn treatments were the highest (Figure 23). While the surface may reach close to 1000 ^{o}C in very intense fires, temperatures of less than 100 ^{o}C may occur at 5cm below, this in part due to the insulating

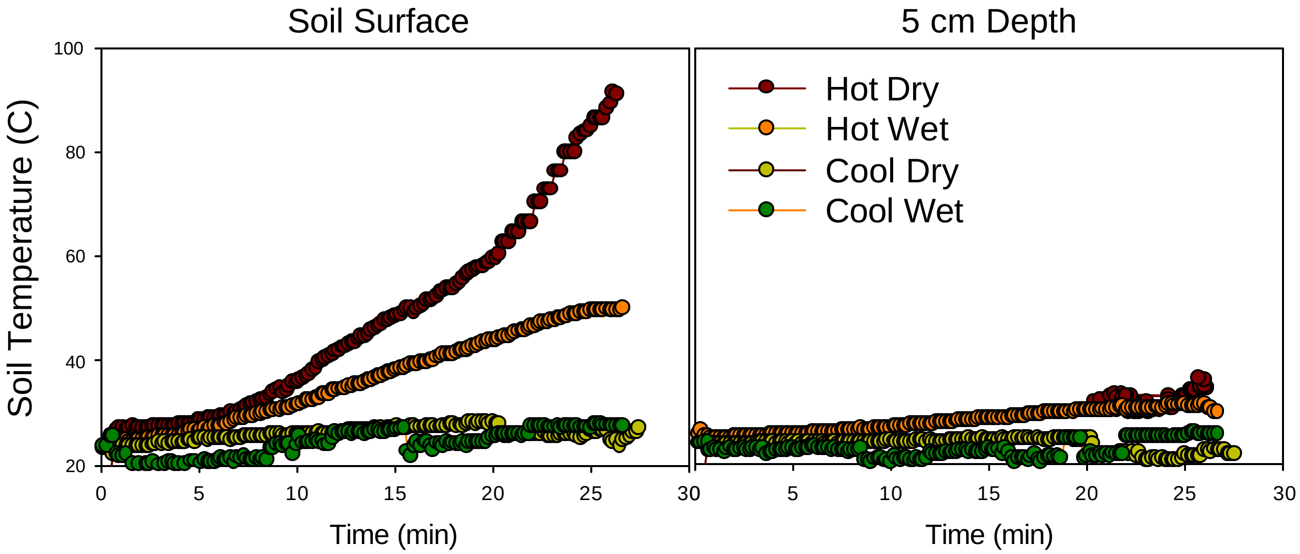


Figure 23. Average temperatures reached at the soil surface and 5cm.

properties of dry soil (Giovanninni et al. 1988). Temperatures attenuated with depth, because the soil is an effective insulator, and temperatures showed little variation at 5 cm below the surface between any of the treatments. The heat dampening properties of soils dramatically decrease the degree to which soil layers below the surface are heated. The 25-minute burn period, followed by extinguishing smoldering particles, limited heat transfer in the soils. Because soil is a good insulator, heat penetrates to depth slowly. Post-fire smoldering of downed vegetation can greatly extend soil heating at depth and intensify fire effects such as hydrophobicity. An increase in burn duration leads to an increase in depth and degree of soil heating (Schimmel and Granstrom, 1996).

Both the degree and depth of soil heating depend on the heat capacity and thermal conductivity of the soil. Wet soils have lower heat conductivity than dry soils due to the high heat capacity of water. Because of water's high heat capacity, temperature gradients in wet soils are far shallower than those in dry soils (DeBano, 1976). Under dry conditions little water is available to buffer heating, consequently available thermal energy directly heats the soil. Soil water buffers the heating effects of fire by sequestering thermal energy for vaporization.

Hydrophobicity

The presence and depth of the hydrophobic layer in each of the 4 burn treatments (hot/cool dry and hot/cool wet) is summarized in Figure 24. Hydrophobicity was found deeper and more often in the hot, dry burn treatments, with a hydrophobic layer at 2 and 4 cm below the surface in 100% of the hot dry treatment profiles and at 6 and 8 cm below the surface in 67% of the hot dry treatment profiles tested. In contrast, in the wet-treatment burns, hydrophobic layers were found in only 33% of the soil profiles at 2, 4 and 6 cm depths, and not at all below 6 cm. The gases responsible for hydrophobic layer formation moved deeper in the hot dry treatments for two reasons: the temperature at which condensation occurs was at a greater depth in the hot dry treatments, due to the considerably higher soil temperatures, and gas movement in the wet soils was restricted due to the greater number of water-filled pores.

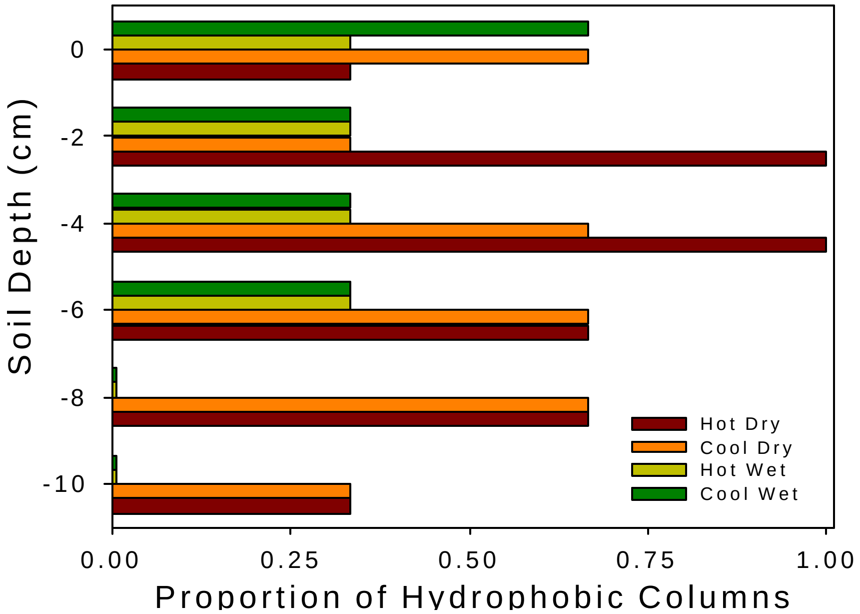


Figure 24. Proportion of columns with hydrophobic layers present at varying depths.

Because of the spatial variability in these properties the idea of a uniformly distributed hydrophobic layer in a natural scenario is greatly over simplified and it is more likely that the development of water repellency is highly variable throughout a burn area. To demonstrate the substantial thermal heterogeneity found during a natural wildfire, we summarized the hottest temperatures recorded for each thermocouple at each depth in both the hot dry and wet treatments (Table 4). These numbers represent the variability found in relatively small soil profiles in our controlled laboratory experiment, and suggest that field conditions would be even more variable. This level of heterogeneity must contribute to the patchy distribution of hydrophobic layers across a landscape following fire.

Depth	Fire Condition	
(cm)	Hot Dry	Hot Wet
0	41.4 – 105.4	32.0 – 82.6
2	37.7 – 86.7	30.9 – 65.2
5	32.1– 40.9	26.4 – 39.0

Table 4. Maximum Temperature Ranges in Burned Soils

FOFEM

The First Order Fire Effects Model (FOFEM) was developed by the Intermountain Fire Research Laboratory to predict the direct, indirect, or immediate quantitative effects on tree mortality, fuel consumption, mineral soil exposure, smoke production, and soil heating of prescribed or wildfire. FOFEM is a mechanistic model, with a system of computation characterized by the laws of physics and chemistry. The model uses algorithms, gleaned from the fire effects literature, that are predictive over a range of conditions. A decision key selects the best available algorithm for the conditions specified by a user, which include soil texture, vegetation and fuel types, % crown fire, amount of duff, soil moisture, region, and season. Alternatively, realistic default values are provided for many inputs, minimizing the data required.

We used the model to explore soil heating with depth over time, which is calculated with heat and vapor flow equations. The parameters we used include interior west region, fall season, lodgepole pine vegetation type, natural fuel, 50% crown fire, typical amounts of fuel types, litter and duff, % rotten logs and log loading distribution using default values set by the model, and a coarse loam soil texture. We varied the moisture conditions, running moderately wet (Figure 25) and dry (Figure 26) scenarios.

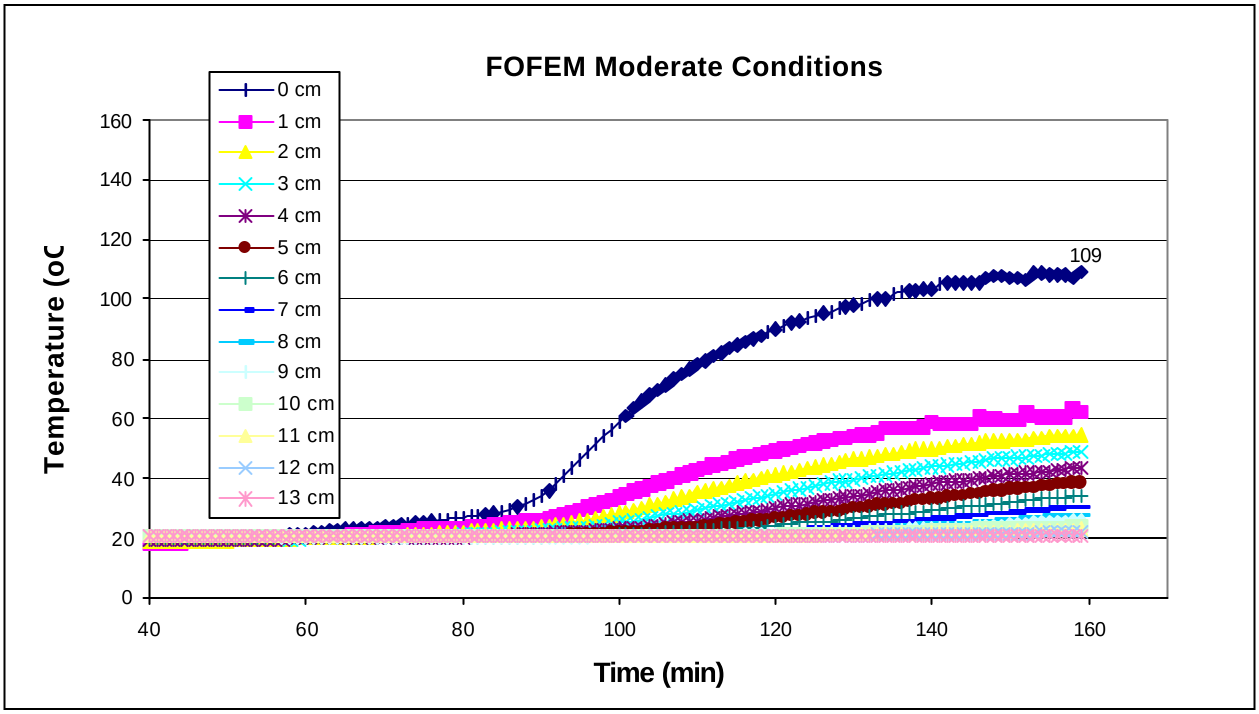


Figure 25. Soil heating with depth over time for moderately wet scenario.

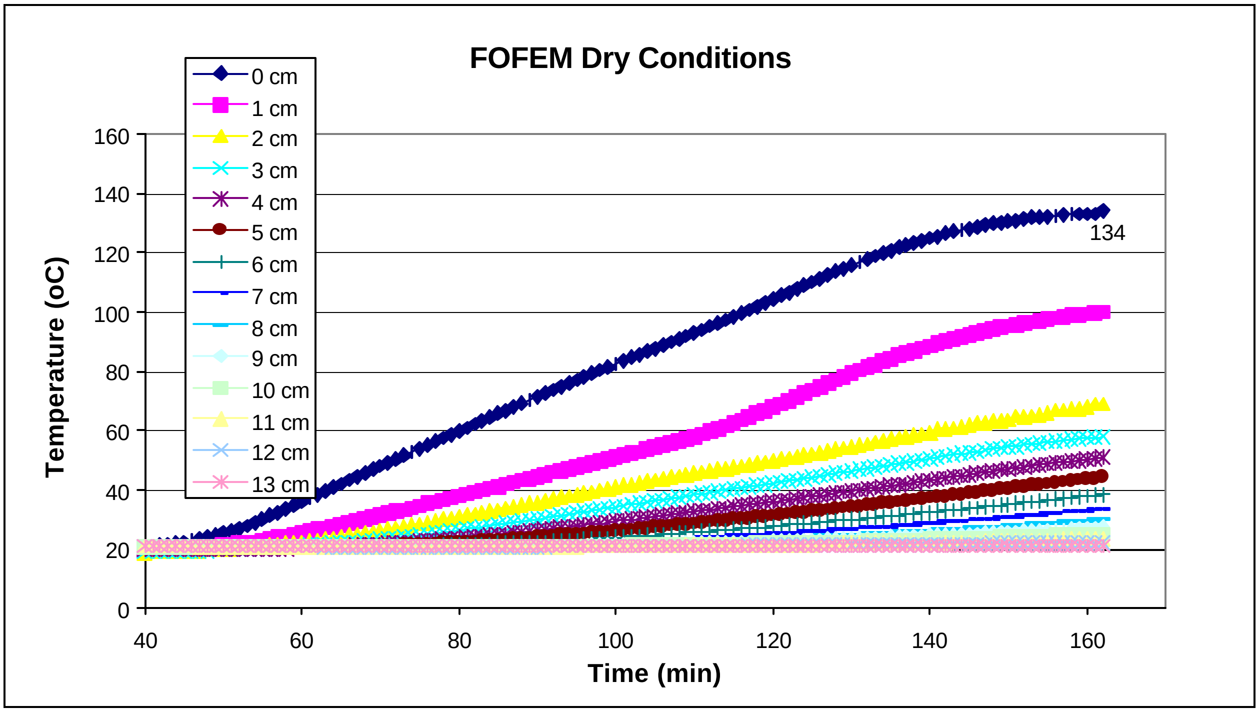


Figure 26. Soil heating with depth over time for dry scenario.

Consistent with the results from our laboratory-burned soils, the highest temperatures occur at the surface, and under dry conditions. Both graphs show a decrease in soil heating with depth, also known as heat amplitude dampening, which demonstrates soil's insulating property.

The model proved useful for demonstrating soil-heating trends, but fails to depict variability inherent to wildfire, which was clearly demonstrated in our "controlled" burn. The model also seemed unresponsive to changes in many of the variables despite its professed ability to select the best algorithm for input values. First-order fire effects form an important basis for predicting secondary effects such as tree regeneration, plant succession, and changes in site productivity. These long-term effects involve interaction with many variables and are not predicted by the model, but insight into the potential of a site post-burn is gained by understanding the first order effects.

Chemical Analysis on Laboratory-Burned Soils:

To test for immediate-post fire effects on soil chemistry, we analyzed laboratory-burned soils, testing the same parameters with the same methods previously described. These parameters were analyzed across the temperature and moisture treatments, and between top and bottom layers of the soil profiles constructed for the laboratory burn. With the exception of potassium, all treatments were not statistically different (Table 5). Potassium was significant in the wet treatments, because the addition of water makes potassium more vulnerable to extraction, we do not believe that this was a fire induced change.

	Hot/Wet	Hot/Dry	Cold/Wet	Cold/Dry
pH	4.9	4.9	5.0	4.9
EC (dS./m)	.24	.22	.29	.25
OM (%)	5.7	5.7	6.6	6.3
NH_4^+ (ppm)	13.2	12.3	12.8	12.1
NO_3^+ (ppm)	1.0	1.0	1.0	1.0
P (ppm)	12.2	8.6	10.8	14.5
K (ppm)	147.6	111.8	147.8	128

Table 5. Mean values for soil parameters

With the exception of nitrate and phosphorus, all soil parameters varied significantly between the upper soil layers, which were most affected by fire and elevated temperatures, and the lower layers, where temperatures did not increase during the burn. Organic matter in the top layer was significantly higher than in the lower layer, in part due to the wood and peat additions to the soil surface during burning. There were no chemical changes with temperature and water treatments, with the exception of potassium with water. We did observe chemical changes with depth. However, due to the methods used and moderate burn temperature attained, it is difficult to attribute these changes to fire influences.

	Top	Bottom
pH	5.2	4.8
EC (dS/m)	0.28	0.23
OM (%)	7.7	4.5
NH_4^+ (ppm)	17.2	7.9
NO_3^- (ppm)	1	1
P (ppm)	13	10.1
K (ppm)	156.8	110.9

Table 6. Mean values for depth

Seed Germination in Laboratory-Burned Soils

Seed germination rates were tested using aqueous extracts derived from the laboratory-burned soils, to determine whether recently burned soils may have an effect on seed germination that field soils sampled one-year post burn would not have. Soil extract preparation, seed germination methods, and the species used were identical to our previously described work. There was no difference in germination rates between any of the treatments, dry (hot and cold,) or wet (hot and cold). This may be due to the relatively short period of time that fires burned on the soil profile, limiting differences between treatments in potential chemical changes that might affect seed germination.

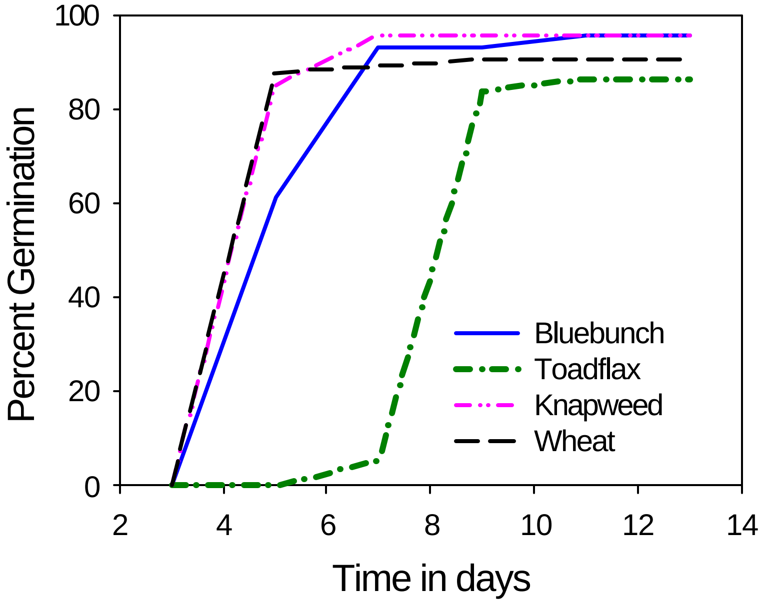


Figure 27. Germination in laboratory-burned soils

Conclusions

The overall goal of this project was to investigate the interactions between fire, soil, and vegetation across a burn and time gradient. One-year post fire, impacts on vegetation and seed bank are evident, however effects vary spatially. In the field we found decreased vegetation cover and species diversity with increasing burn severity, and patchy distribution of plant cover. The seed bank contained fewer seeds present in soils of the burned areas, as a result of combustion of the litter layer and lethal temperatures reached in the severely burned soils. Even with that decrease, there was still a considerable number of seeds stored in the soils. Those seeds, and roots from plants such as *Vaccinium*, that are able to resprout after fire, represent natural recovery systems that can reduce post-fire erosion.

Fire effects on soil chemistry are also evident one-year post fire. Organic matter combustion resulted in elevated ammonium and phosphorous levels, while organic matter and potassium levels decreased. The magnitude and extent of these changes, and their subsequent impact on revegetation, are highly variable across the landscape. Potential impacts on vegetation are dependent on topography, climate, nutrient movement, and microbial communities, as well as individual species' nutrient requirements.

Fire effects on seed germination and plant growth are complex and evident for only some of the species studied. To address management concerns regarding invasive species colonization, we examined both native and invasive species' germination and emergence. Both germinated at similar rates, and in some cases the native species germinated at a higher rate than the invasive species, suggesting that invasive species do not necessarily have the advantage in recently burned environments. Bluebunch wheatgrass produced greater biomass in severely burned soils as compared to unburned soils, while knapweed and milkvetch biomass did not differ between burn severities. Both the biomass and emergence data suggest a complex relationship between physical and chemical fire effects and plant reestablishment. This finding may be important in establishing vegetation and erosion practices following a fire.

In conducting laboratory burns, we documented soil's capability of insulating subsurface layers from the extreme temperatures reached at the surface. This insulating ability can protect seeds stored a few centimeters below the surface, protecting an important source of natural revegetation. This observation is useful when considering costly revegetation methods versus the natural regenerative capabilities of the system.

We also documented the formation of hydrophobic layers more often and at greater depths in the dry treatments than in the wet treatments. One possible explanation for this is that there were a greater number of air-filled pores in the dry soil allowing the gases responsible for the formation to move deeper in the profile. Another is that temperatures needed for gaseous condensation of the complex compounds were found closer to the surface in the wet treatments due to the overall lower temperatures recorded. Hydrophobicity is closely related to erosion, mass wasting, and soil resource loss, making its formation a critical soil response following fire. By further studying and understanding the mechanisms driving hydrophobicity and complicating factors such as soil moisture, future erosion losses and system degradation could be minimized.

A recurring point in this study has been the great amount of variation existing in nature. The Purdy Fire burned nearly 3,000 acres in one day (September 27, 2001), with a large amount of heterogeneity in intensity and severity across the 3,000 acres. Even in the controlled setting of a laboratory burn, a high amount of temperature variation and heating variability (Table 4) was observed within the soil profile. This leads us to believe that the large amount of spatial heterogeneity found in a wildfire may result in pockets of soil resources that are not as heavily impacted, so can serve as a source of seeds and soil biota for regenerating forest systems.

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Germination in Aqueous Extracts

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