Below-ground Impacts of Pile Burning in the Inland Northwestern U.S.A.

Project Title: Below-ground Impacts of Pile Burning in the Inland Northwestern U.S.

Final Report: JFSP Project Number JFSP #11-1-8-2

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I. Abstract

Forest restoration efforts require thinning operations to reduce tree density, wildfire risk, or insect and disease conditions to improve ecosystem processes and function. However, one issue with the thinned stands is to dispose of the residues. Slash pile burning is currently used on many forest sites as a preferred method for residue disposal because they can be burned at various times of the year and are usually more controlled than broadcast burns. In some cases, fire can be beneficial to site conditions and soil properties, but often large slash piles, with a concentration of a large amount of wood, needles, forest floor, and sometimes mineral soil, can do irreversible damage. We examined the effect of burning slash piles on the fire temperature pulse and changes in soil chemical, physical, and biological changes. Findings from our research highlight (1) the importance of soil texture which alters how soil moisture is held in the mineral soil and its' ability to temper heat movement into the mineral soil, (2) soil biological function (fungi and bacteria) becomes very limited after very hot (>500°C) fire condition, (3) soil chemical properties were altered after the fire and had not returned to pre-burn conditions at the end of our study period.

II. Background and Purpose

Many forest stands in the western United States are in need of restoration for a variety of attributes (e.g., fire regimes or watershed health) after 100 years of fire suppression or lack of harvesting activities. Pre-commercial and commercial thinnings along with biomass-to-energy harvests contribute to large amounts of slash material, which is commonly disposed of by piling and burning. Although slash burning is an effective method for disposing of the unmarketable material, it can produce unwanted soil impacts (Jiménez-Esquilín et al. 2007; Massman 2004). Soil impacts from fire can be highly variable because of differences in soil texture, fuel type and loading, and weather conditions during burning (e.g., Dyrness and Youngberg 1957; Frandsen and Ryan 1986; Hardy et al. 1996). Often, slash piles leave only localized soil impacts, but depending on the size of the pile, the amount and type of fuel, and the distribution of piles within an activity area, impacts could be at a larger scale.

Considerable information is available on changes in soil physical and chemical properties as a result of burning slash piles (*e.g.* increased pH and levels of base cations, decreased soil C, N, P, organic matter (OM), and aggregate stability (Neary et al. 1999)). However, much less is known soil biological changes caused by pile burning, and on heat flux into the soil as affected by different fuel sources and loadings, and fuel and soil moisture contents. Most of these studies were short-term (≤1-2 yrs after the burn), and we could find none that looked at long-term impacts on soil properties and subsequent stand development. Therefore, we propose to evaluate heat pulse profiles under and around burn piles on differing soil types in Inland Northwestern forests, and how they affect soil chemical, physical, and biological properties. Slash piles will be burned under a range of moisture conditions, use locally available logging slash, and will represent operational slash piles created during harvesting. Longer-term impact (>35 years) of slash pile-burning on soil and stand development will also be assessed in forests in northwestern Montana, where this site preparation is commonly used following clear-cut harvesting.

Slash piles have been burned on National Forests as an economical way of disposing slash following timber harvesting operations. The impact of these piles on below-ground processes is highly variable, and can lead to relatively small impacts for a short period of time, or long-term residual damage. To date there has been little work that elucidates how typically built piles (*e.g.*, standard management practices for each forest) might alter the combined below-ground physical, chemical, and biological properties because of different heat pulse signatures. *In-situ* fire behavior measurements are also a critical component of assessing radiant and convective energy transfer and impacts from the fire (Jiménez-Esquilín et al. 2007).

While there have been studies on the effect of slash burning on soil chemical and physical properties (e.g. Covington et al. 1991; Oswald et al. 1999; Kolb et al. 2004), nearly all of them have been short-term and "retrospective", in that no measurements were taken on the piles before burning, such as total pile biomass or wood and soil moisture content. Much less is known on soil biological responses to pile burning, and the few studies conducted usually focused on mycorrhizae (Korb et al. 2004; Owen et al. 2009; Haskins and Gehring 2004). However, little has been done to determine how pile burning can alter basic soil microbial processes, such as decomposition. Changes in the rate of organic matter (OM) decomposition after a fire can indicate a change or loss of important soil microorganisms, such as white-rot and brown-rot fungi and available water for regeneration. Preliminary data from a study we conducted on the Flathead National Forest indicates a shift in soil microbial community structure within slash pile burn areas (Page-Dumroese unpublished data). After harvesting, white-rot fungi decomposed aspen (*Populus tremuloides*) stakes at a similar rate after broadcast fire and slash pile burning. In contrast, brown-rot fungi decomposed pine stakes (*Pinus taeda*) at a much slower rate within the burn pile areas than where the logging residue was broadcast burned. While these results are limited in scope, they indicate a shift in microbial community structure within burn piles, which is likely caused by different soil heat pulse profiles during burning.

Soil quality standards within the U.S. Forest Service limit the areal extent of detrimental soil impacts after harvesting and site preparation (Page-Dumroese et al. 2009). Extensive use of burn piles within an activity area can exceed the soil quality standard of 15% areal extent if the burn piles cause detrimental changes in soil productivity. Evaluating burn piles for detrimental impacts (change in soil structure, reduced infiltration, reduced vegetative growth, color change in the mineral soil, loss of OM in the mineral soil) is critical for maintaining site productivity and reducing invasive species.

The specific objectives of this study were to: (1) elucidate how slash pile burning on different soil textures at different slash and soil moisture conditions (spring burn vs. fall burn) affects heat moving into the soil, (2) how the heat pulse impacts soil chemical (basic cations, pH, N, C, P), physical (OM), and biological (wood decomposition) properties and (3) determine changes in soil fungi in old (35 yr) slash piles on the Flathead National Forest which have limited to no tree regeneration.

III. Site Descriptions and Methods

Site descriptions and pile measurements*:* We used three sites to determine the impact of fall and spring burning on soil temperature and the associated changes in chemical, physical, and biological properties.

Lubrecht Experimental Forest: The Lubrecht Experimental Forest is located approximately 45 miles NE of Missoula, MT (46°53´32N, 113° 26´ 04W). Two sites were selected at this forest one with a coarse-textured soil in a mixed ponderosa pine (*Pinus ponderosa* Douglas ex Laws.) and Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) forest and one with fine-textured soil in a ponderosa pine forest. The fine-textured site had a skeletal soil with 40-60% coarse-fragment content. Harvest residues were grapple piled just before burning. At this site six piles were created on each soil type and three piles were burned in the spring and three in the fall by University of Montana personnel, as ambient conditions allowed.

Priest River Experimental Forest: The Priest River Experimental Forest is located in northern ID (48°18´59N, 116°51´54W). One site was selected and is on a volcanic ash-cap soil (silt loam texture). Three piles were created with a grappler after harvesting a mixed conifer (white pine (*Pinus monticola* Douglas ex D.Don), western larch (*Larix occidentalis* Nutt), grand fir (*Abies grandis* Douglas ex D. Don Lindl), and Douglas-fir. As is typical of sites on the nearby Idaho Panhandle National Forest, slash piles were burned only in the fall.

Pringle Falls Experimental Forest: This site is located south of Bend, OR on coarse-textured pumice soils (43°44´19N, 121°38´33W). This site is part of a larger study on 'Mega-logs' developed by Oregon State University and the Pacific Northwest Research Station. At this site we selected 3 areas that had been burned severely (emulating a fall burn (HSB- high severity burn)) and burned lightly (emulating a spring burn (LSB – Low severity burn).

At Lubrecht and Priest River Experimental Forests, thermocouples were installed at four locations under one pile (center and three equi-distant locations under the edge of the pile) and at three locations outside the pile where thermocouples were placed 1, 2, 3, and 5 m from the edge. Under the pile, thermocouples were placed at 0, 2, 5, 10, 15, 30, and 50 cm depth in the mineral soil. Outside the pile, thermocouples were placed at 0, 2, 5, 10, 15, and 30 cm depth in the mineral soil. For each study site a control (unburned) site was also selected and thermocouples were inserted into the mineral soil at depths of 0, 2, 5, 10, 15, and 30 cm. At the Pringle Falls Experimental Forest, thermocouples were installed under each burn type at depths of 0, 5, 10, and 30 cm. At each site the volume and biomass of each slash pile at each site was measured following the methodology of Hardy (1996).

Before and after burning, soil bulk density samples were collected within each slash pile and outside the pile in the control at three depths (0-10, 10-20, and 20-30 cm). Bulk density was collected using either a corer to obtain a known volume of soil or, if the soil was rocky, a small pit was excavated, filled with polyurethane expanding foam, covered with a piece of cardboard (Page-Dumroese et al. 1999). The core was collected approximately 24 h later after the foam had dried. Volume for the excavated pit was determined on the foam core by water displacement. Soil from both the core and pit samples was oven dried and weighed.

Summary of energy measurements made on pile burns: The primary sensor package used for these measurements is termed the Fire Behavior Flux Package (FBP). It measures 27 cm by 15 cm by 18 cm and in its current configuration weighs approximately 5.3 kg (fig. 1). A 12 volt 2.2Ah sealed lead acid battery or 8 AA dry cells provide power to the logger. A separate 8 AA dry cell battery array provides power for the flow sensors.

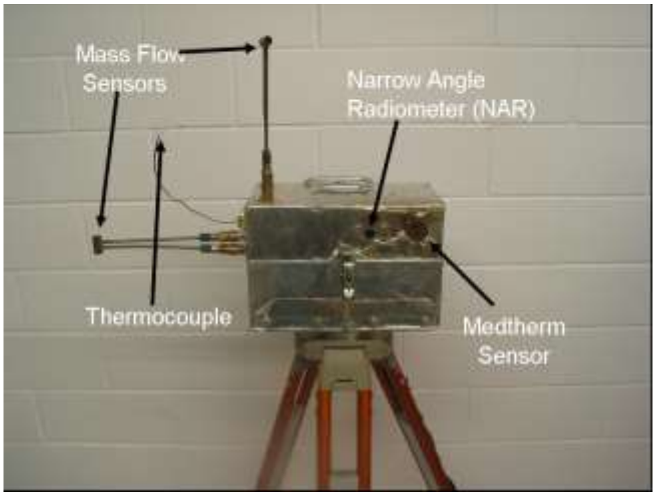

Figure 1--Photograph of Fire Behavior Package.

The dataloggers used are Campbell Scientific® model CR1000. The dataloggers are capable of logging over one million samples, providing 20 hours of continuous data logging at 1hz. This logger is thermally stable. The FBP incorporate a Medtherm® Dual Sensor Heat Flux sensor (Model 64-20T) that provides incident total and radiant energy flux, a type K fine wire thermocouple (nominally 0.13 mm diameter wire) for measuring gas temperature, a custom designed narrow angle radiometer (Butler 1993) to characterize flame emissive power, and two pressure based flow sensors (McCaffrey and Heskestad 1976) to characterize air flow. Table 1 provides details about individual sensors and their engineering specifications.

Table 1. *In situ* Fire Behavior Package (FBP) Specifications

Narrow Angle Radiometer	
Sensor	20-40 element thermopile
Spectral Band of Sensor	0.15 – 7.0 µm with sapphire window
Field of View	~4.5º controlled by aperture in sensor housing
Transient Response	Time constant of sensor nominally 30msec
Units of Measurement	Calibrated to provide emissive power of volume in FOV in kW-m^{-2}
Total Energy Sensor	Medtherm Corp® Model 64-20T Dual total Heat Flux Sensor/Radiometer
Sensor	Schmidt-Boelter Thermopile
Spectral Band of Sensor	All incident thermal energy
Field of View	~130º controlled by aperture in sensor housing
Transient Response	< 290msec
Units of Measurement	Total heat flux incident on sensor face in kW-m^{-2}
Hemispherical Radiometer	Medtherm Corp® Model 64-20T Dual total Heat Flux Sensor/Radiometer
Sensor	Schmidt-Boelter Thermopile (Medtherm Inc)
Spectral Band of Sensor	0.15 – 7.0 µm with sapphire window
Field of View	~130º controlled by window aperture
Transient Response	< 290msec
Units of Measurement	Radiant energy incident on sensor face in kW-m^{-2}

Air Temperature	
Sensor	Type K bare wire butt welded thermocouple, new, shiny, connected to 27ga lead wire
Wire Diameter	0.13mm
Bead Diameter	~0.16-0.20mm
Units of Measurement	Degrees Celsius
Air Mass Flow	
Sensor	SDXL005D4 temperature compensated differential pressure sensor
Pressure Range	0-5 in H_2O
Sensor Design	Pressure sensor is coupled bidirectional probe with ±60º directional sensitivity.
Units of Measurement	Calibrated to convert dynamic pressure to velocity in m-s^{-1} assuming incompressible flow
Sensor Housing Dimensions	150× 180 × 270 (mm)
Housing Weight	7.7 kg
Insulation Material	Cotronics Corp® 2.5cm thick ceramic blanket
Tripod Mount	½ inch female NCT fitting permanently mounted to base of enclosure.
Power Requirements	12V DC
Power Supply	Rechargeable Internal Battery
Data Logging	Campbell Scientific Model CR1000
Sampling Frequency	Variable but generally set at 1 Hz
File Format	ASCII

Sensors were placed along three transects extending radially away from the edge of the pile. Some sensors were place with the sensors "looking" upward and others were oriented with the sensors "looking" horizontally at the pile. Thus the "V" and "H" orientation in the tables. Sensors with the V designation were looking upward, while those with the H configuration were facing the pile. Upward facing sensors were place so that upper surface (sensing surface) was located level with the ground surface. Horizontally facing sensors were place on the ground with the primary sensors approximately 20 cm above the ground surface.

Table 1 presents a summary of pile and flame observations for each burn. It is surprising just how short the flaming combustion duration is for what are moderately large piles. Flame heights varied from 5 to 10 m. Further measurements of temperature in the flames as well as upward directed energy flux would be informative in terms of characterizing the potential impact of heat from burning piles on surrounding vegetation

Post-fire measurements (recent burns): In each slash pile and control (2 replicates/site) a wood stake decomposition study was established. Standard substrates for the wood stakes were pine (*Pinus taeda* L.) and aspen (*Populus tremuloides* Michx.) since they are widely used in soil tests of wood preservatives and decomposition (Jurgensen et al. 2006; Gonzales et al. 2008; Woodward et al. 2011). Installation generally followed the protocol outlined in Jurgensen et al. (2006). In each treatment area, 25 stakes of each species were installed into the mineral soil (stakes were 2.5 cm^2 x 20 cm long). To insert the stakes, the forest floor (only in control plots) was carefully removed from the soil surface and the stakes inserted vertically in square holes (2.5 cm^2) made with a slide hammer tool. Stakes were placed approximately 30 cm apart. The stakes were placed so that the top of the stake was level with the mineral soil surface and the forest floor replaced. The top of each stake placed vertically in the mineral soil was treated with a wood sealer to prevent wood moisture loss after installation. In addition, a similar number of stakes (25 of each species; 2.5 cm^2 x 15 cm long) were placed horizontally on the mineral soil surface and covered with forest floor (unburned area). Another set of 25 stakes (2.5 cm^2 x 15 cm long) of each species were placed on top of the forest floor (unburned) and on top of the mineral soil (wildfire). A total of 50 stakes of each species at each National Forest were installed at each soil position and site treatment. In the subsequent years, five stakes of each species were removed from each of the subplots and soil positions (from the mineral soil, on the mineral soil surface or forest floor, and at the interface between mineral soil and forest floor at each site) until all of the stakes are removed in 2017. Initial mass of each stake and a control (not placed in the field) was taken prior to deployment of the stakes. Stakes placed on or in the forest floor were secured in place with stainless steel landscape staples (Forestry Suppliers Inc., Jackson, Mississippi).

Stakes were sent to the School of Forest Resources and Environmental Science at Michigan Technological University for processing. In the laboratory, all the wood stakes dried at 105 °C for 48 h and weighed. To assess decomposition changes with depth into the mineral soil, 2.5 cm^2 blocks were cut at 2 depths (5 and 15 cm from the top of the stake). Samples were dried, weighed and compared to their respective control section (Jurgensen et al. 2006).

In addition, in each burn area and control, ion resin capsules (Unibest Resin Capsules, Bozeman, MT) were installed at depths of 5, 10, and 20 cm. These resin capsules are collected every six months determine nutrient exchange in the mineral soil solution. Soil temperature and moisture sensors were installed and are collecting a measurement every 4 hours at depths of 10 and 20 cm within the mineral soil. Soil pH was measured on a 2:1 water:soil paste, organic matter by loss-on-ignition at 375°C for 8 h, and soil texture using the hydrometer method.

Post-fire measurements (old slash piles)

On the Flathead National Forest in northwestern Montana many locations had slash piles burned in the 1960's. These piles were created by dozer piling forest residues and forest floor material and then fall burning. We selected 3 replicate sites to install our wood decomposition study (see above) and collect similar soil measurements as above. Soils are a mixed volcanic ash/glacial till soil (skeletal soils with 20-40% rock fragment content). On burn plots where plant species have regenerated and in the control areas, plant cover was estimated using the Cover Management Assistant (Steinfeld et al. 2012). Soil temperature and moisture will be collected every 4 hours.

Soil samples (n = 28; each 0.25 g fresh weight) were collected along a transect positioned from the center of each of three slash piles through to the adjacent forest interior on 24 June 2014 in the Flathead National Forest (Kalispell, MT). DNA was extracted from each sample using the PowerLyzer® PowerSoil® DNA Isolation Kit (MO BIO Laboratories, Carlsbad, CA, USA). Yields were measured via Qubit® fluorometric quantitation (Life Technologies, Grand Island, NY, USA). Composition of the microbial community (bacteria and archaea) was determined using double-barcoded 16S (v1v3 and v4v5) amplicons generated from replicate PCR and sequenced using the Illumina® MiSeq platform (Illumina, San Diego, CA).

III. Key Findings

Objective 1: elucidate how slash pile burning on different soil textures at different slash and soil moisture conditions (spring burn vs. fall burn) affects heat moving into the soil

- Temperature differences among site, soil texture, and burn season illustrate the importance of ensuring the soil is moist before burning. Peak burn temperatures were highest after fall burning and soil heating was generally lowest in the spring. Soil heating was not as prolonged after spring as compared to fall burning. In addition, coarse-textured soil temperatures were higher than the burn piles on fine-textured soil.

- Smoldering of wood likely contributes to the long residence time of soil heating. Fall burning resulted in drier surface material and therefore a longer time that heat is able alter soil chemical and biological properties. Although soil temperatures were not high enough to sterilize the soil, short-term changes in soil properties may alter plant reestablishment.

Objective 2: how the heat pulse impacts soil chemical (basic cations, pH, N, C, P), physical (OM), and biological (wood decomposition) properties

- Table 2 illustrates the relative soil changes as a result of pile burning. Soil moisture appears to control the losses of organic matter and soil carbon within the top 30 cm of mineral soil. In addition, pH changes associated with pile burning are less when soil moisture is high. We also analyzed each soil pre- and post-burn for changes in soil texture. We were able to detect small changes in soil texture that are likely the result of the disassociation of organic matter from the mineral soil particles. While this was not important for our slash piles, it may be an important soil change for larger slash piles that have the potential to burn hotter and longer.

Table 2. Mean slash pile size, flame height and duration, and relative post-fire changes (percent) in soil properties to a depth of 30 cm after slash pile burning relative to control soil for fine- and coarse-textured soil burned in spring or fall.

Site	Soil Texture	Burn season	Pile size*	Peak flame height	Flame duration	Soil Moisture at ignition	pH	OM	C	N
			- Mg -	-m-	-min-	-percent-	Percent change from unburned control			
Lubrecht EF	Fine	Spring	9.6	9	90	33.5	+9	+10	+18	+17
		Fall	6.8	.	.	12.6	+12	-39	-25	-3
	Coarse	Spring	7.2	8	250	16.1	+9	-49	-50	-56
		Fall	9.8	10	180	11.2	+25	-64	-57	-63
Priest River EF	Fine	Fall	5.6	10	120	26.5	+2	-16	-5	-8
Pringle Falls EF	Coarse	Spring (LSB)	3.2	.	.	17.2	+5	-22	-24	-14
		Fall (HSB)	3.3	.	.	12.3	+13	-17	-44	-22

*Pile size was calculated by the Pile Size Calculator (Hardy, 1995)

- In our study, pile size was relatively small and did not influence changes in soil C, N, or OM as much as season of burning and soil texture. For example, at Lubrecht Experimental Forest, fall burning on coarse-textured soil resulted in more organic matter, C, and N loss as compared to spring burning on that soil texture. Losses in the coarse-textured soils were generally greater than their fine-textured. Interestingly, the spring burn on fine-textured soil at Lubrecht Experimental Forest had gains in soil organic matter, C and N. This is likely due to mixing of wood and charcoal into the soil as the piles were burning low.

- Soil nutrient bioavailability using ion-exchange techniques are frequently used to monitor soil chemistry for comparative purposes. This aspect of our study was initiated to gauge soil nutrient changes for NO^-_3, NH^+_4, ortho-P, K^+, Ca^{+2}, Mg^{+2}, Fe, Mn, Na^+, and S after slash pile burning. Summarized data are shown in Table 3. Clearly soil type and burn season alter nutrient availability, but the data is not consistent. For example, fall burning on fine-textured soils resulted in a large increase in Na^+, however there was only a slight increase in the nutrient on the coarse-textured soil. We also note a very large increase in NO_3^- on fine-textured soil after fall burning; whereas fall burning on coarse-textured soil saw a moderate increase in NO_3^-. Interestingly, there was a decrease in NH^+_4 in the fine-textured soil after burning during both seasons, but an increase in NH^+_4 on coarse-textured soil.

Table 3. Mean resin availability of soil nutrients at the Lubrecht Experimental Forest as affected by slash pile burning season and soil texture.

Soil Texture	**Burn season**	**NO_3^-**	**NH^+_4**	**Ca^{+2}**	**Mg^{+2}**	**K^+**	**Ortho -P**	**Fe**	**Mn**	**Na^+**	**S**
						----- µg/capsule ----					
Fine	Unburned	1.0	23.3	105.4	21.3	20.3	.1	0.9	0.9	18.2	8.2
	Spring	73.5	2.9	446.4	115.4	187.4	54.3	0.9	0.5	14.2	86.1
	Fall	306.7	3.1	393.5	104.5	154.6	19.6	0.5	2.1	64.7	45.8
Coarse	Unburned	0.5	2.6	157.7	22.0	53.1	8.2	2.5	1.5	3.7	8.4
	Spring	29.5	4.9	257.9	41.8	107.9	12.6	1.5	1.7	9.4	77.4
	Fall	33.4	23.6	144.2	27.7	91.9	5.2	0.9	1.7	8.8	56.4

- Using wood stakes as a surrogate for determining a change in soil fungal activity shows that aspen (*Populus tremuloides*) wood decayed almost 70% faster after fall slash pile burning on coarse-textured soil. Pine (*Pinus taeda*) stakes were also affected, but changes in decomposition rates were smaller. Our data points to a shift in soil microbial community structure within slash pile burn areas. White-rot fungi decomposed aspen stakes at a similar rate after broadcast fire and slash pile burning. In contrast, brown-rot fungi decomposed pine stakes at a much slower rate within the burn pile areas than where the logging residue was broadcast burned.
- Because decomposition within our burn piles was accelerated as compared to the control soil heating was likely not severe enough to sterilize the soil and that the increase in NO_3^- and NH_4^+ in the mineral soil likely accelerates the decay process.
- The first pile that was instrumented with heat flux sensors occurred at Lubrecht on November 4, 2011. Figure 2 presents the measurements. Clearly the horizontally facing sensors receive higher energy loads than the upward facing sensors. I would expect that energy flux to the ground surface would lie between the values captured by the two sensor orientations, with any bias occurring to the horizontally facing sensors. Regardless the total energy flux to the ground was relatively low for all burns. The most energy that can be received on the earth from the sun is about 0.8 kW/m^2. Thus values measured around these piles was nominally less than 10 times the solar heating maximum. Duration of heating above 3 kW/m^2 was less than 40 minutes for all piles. This same response was repeated in all subsequent piles.

Table 4. Heat flux data from the fall burn on fine-textured soil at the Lubrecht Experimental Forest.

Logger #	Transect	Distance	Orientation	comments	Peak total	Peak Radiative	Peak Conv	NAR	Peak temp
		-m-				---kW/m^2---			-°C-
09	N	1	V		6				310
01	N	2	V		6				290
15	N	3	V	N/D					
2	N	5	V		1.7				150
07	E	1	V		3.6	3.2	0.4		250
05	E	2	V		2.1	2.1	0		150
13	E	3	V		1.4	0.9	0.5		140
12	E	5	V		0.9	0.9	0		120
10	SW	1	V		2.2	2	0.3		220
14	SW	2	V	N/D					
11	SW	3	V		1	0.9	0.1		200
16	SW	5	V	N/D					
03	E	1	H		7	2.1	1.1		250
08	E	2	H		7	2	1		290
06	E	3	H		6	2	1		240
04	E	5	H		4	2	0.2		250
17	SW	2	H		4.2	3.3	1	130	250

Figure 2. Lubrecht Experimental Forest burn pile.

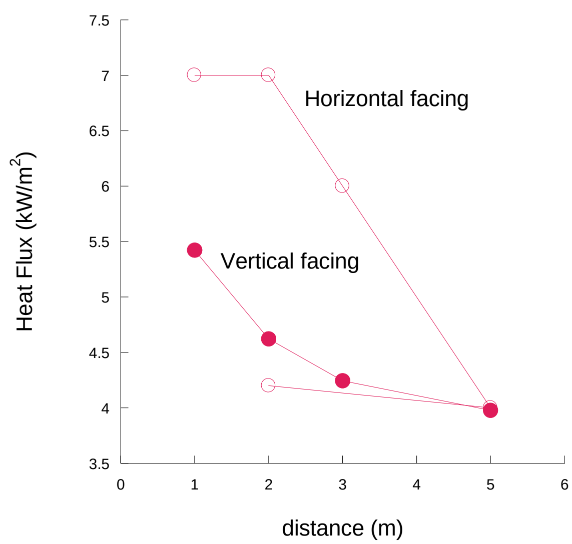

Figure 3. Heat flux from the fall burn on fine-textured soil at Lubrecht Experimental Forest.

Table 5. Heat flux data from the spring burn on fine-textured soil at the Lubrecht Experimental Forest.

Logger	Transect	Distance	Orientation	comments	Peak total	Peak Radiative	Peak Conv	NAR	Peak temp
- # -		- m -				--- kW/m^2 ---			-°C-
16	N	1	V		4.5	4.1	2		31
13	N	2	V		2.8	0.8	2		24
04	N	3	V	No data					
05	N	5	V		0.8	0.2	0.6		17
03	E	1	V		3.8	1.8	2.5	6	22
18	E	2	V		3.2	1	2.1		27
17	E	3	V		2.7	0.2	2.5	14.5	24
09	E	5	V		0.9	0.8	0.1		20
15	SW	1	V		2.1	1.1	1		28
07	SW	2	V		2.4	1	1.4		22
11	SW	3	V		1.2	1	.1	6	18
10	SW	5	V		0.6	0.2	0.3		22
01	N	1	H		7.8	7	2.8		90
14	N	2	H	No data					
06	N	3	H		4	2	2		22
02	N	5	H		2.5	1.8	0.8	125	20
12	SW	1	H		7	6	1		30

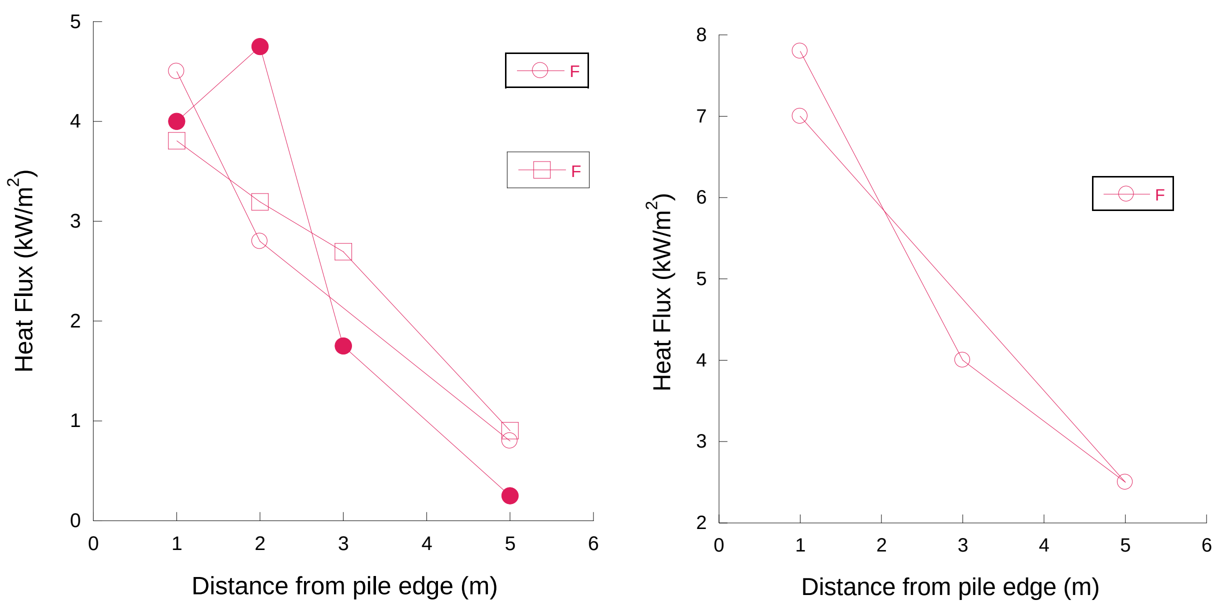

Figure 3. Heat flux from spring burn on coarse-textured soil at Lubrecht Experimental Forest. Left plot is total heat flux to upward facing sensors; right plot is total heat flux to horizontally facing sensors.

Table 6. Heat flux data from the fall burn on coarse-textured soil at the Lubrecht Experimental Forest

Logger	Transect	Distance	Orientation	comments	Peak total	Peak Radiative	Peak Conv	NAR	Peak temp
- # -		- m -				---- kW/m^2 ----			-°C -
02	1	1	V	N/D					
21	1	2	V	N/D					
04	1	3	V	N/D				2.5	
08	1	5	V	N/D					
03	4	1	H		6.5	6	0.1	65	300
07	4	2	H		3	2.8	0.1	140	200
09	4	3	H		2	1.8		50	170
19	2	1	V		0.5	0.5	0		120
17	2	2	V	N/D					
16	2	3	V	N/D					
12	2	5	V	N/D					
20	3	1	V		0.8	0.8	0	1	170
05	3	2	V	N/D					
11	3	3	V	N/D					
18	3	5	V	N/D					

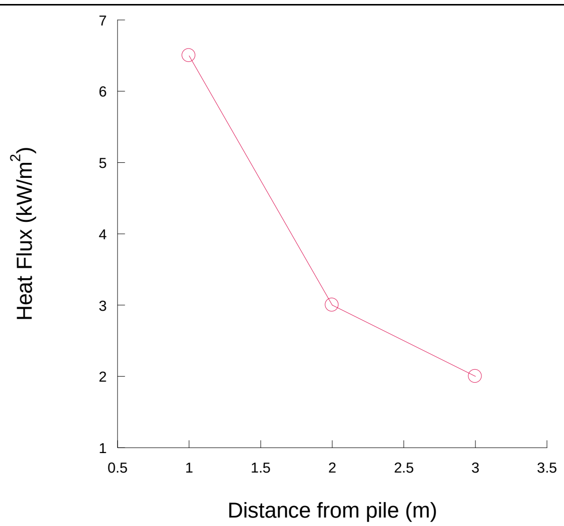

Figure 4. Heat flux from the fall burn on coarse-textured soil at the Lubrecht Experimental Forest.

Figure 5. Fall burns on coarse-textured soil at Lubrecht Experimental Forest.

Table 7. Heat flux from spring burn on coarse-textured soil at the Lubrecht Experimental Forest.

Logger #	Transect	Distance	Orientation	comments	Peak total	Peak Radiative	Peak Conv	NAR	Peak temp
		-- m --			---- kW/m^2 ----				- ° C -
10	1-360	1	H		9.3	9.2	2	4	315
02	1	2	H		5.7	4.2	2	5	102
12	1	3	H		4.3	4.1	0.4	3.4	110
13	1	5	H		2	1.4	0.6	4.3	28
05	2-54	1	H		16	13	6	45	615
07	2	2	H		7.6	7	1	7	830
09	2	3	H		3.7	3.3	0.6	35	34
18	2	5	H		2.6	2.2	0.5	25	33
11	3-280	1	H		9.4	10.4	1	63	71
06	3	2	H		7.2	4.7	3	55	62
16	3	3	H		6	6	1	24	76
19	3	5	H		3.2	2.6	0.6	9	33
04	4-180	1	V		17	8.4	15	7	1500
21	4	2	V		7	5	2	5	115
17	4	3	V		4	3	1.4	13	92
15	4	5	V		3.3	0.8	3.2	1.35	40

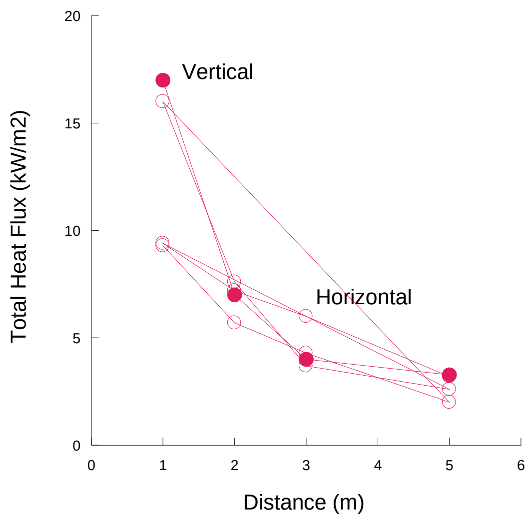

Figure 6. Heat flux from spring burn on coarse-textured soil at Lubrecht Experimental Forest.

Table 8. Heat flux from a fall burned pile on fine-textured soil at the Priest River Experimental Forest.

Logger #	Transect	Distance (m)	Orientation	comments	Peak total (KW/m^2)	Peak Radiative (KW/m^2)	Peak Conv (KW/m^2)	NAR (KW/m^2)	Peak temp (C)
04	1-120	1	H		1.7	1.2	0.5	5	1500
22	1	2	H	N/D					
19	1	3	H		1.6	1.3	0.5	31	29
21	1	5	H	N/D					
01	2-350	1	V		0.3	0.2	0.2	0.8	1500
16	2	2	V		0.4	0.2	0.4	0.9	1300
17	2	3	V	N/D					
13	2	5	V	N/D					
08	3-280	1	H		2.2	2.3	0.2	2.3	40
09	3	2	H		1.7	1.3	0.4	7.5	25
06	3	3	H		1.2	0.7	0.5	4.6	20
05	3	5	H		0.6	0.5	0.1	3.7	11
07	4-180	1	H		1	0.3	0.9	1.6	27
18	4	2	H		0.6	0.4	0.6	2	47
20	4	3	H		0	0	0	0	10
12	4	5	H	N/D					

Figure 7. Fall burned pile at the Priest River Experimental Forest.

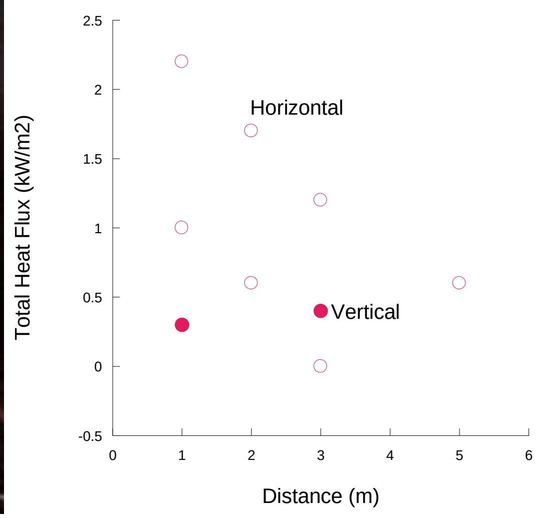

Figure 8. Heat flux from a fall burned pile on fine-textured soil at the Priest River Experimental Forest.

Objective 3: Determine changes in soil fungi in old (35 yr) slash piles on the Flathead National Forest which have limited to no tree regeneration.

- In our survey of 35-year old slash piles, we found the burn scars dominated by grasses, non-native, and invasive species whereas areas outside of the old burn area was dominated by trees, shrubs, and forbs. This shift in above-ground species also translates to changes in microbial structure and function.
- In these slash piles, the soil was sterilized. There are few native species, no trees, and little decomposition of residual woody material within the soil that was buried during pile construction. Our reconstruction of these piles indicates that they were dozer-piled and much of the surrounding forest floor was likely incorporated into the piles. Piles were fall burned when soil moisture was low.
- Both 16S loci (v1v3 and v4v5) revealed rich microbial communities with consistent patterns associated with sample depth and transect position. More than 800 taxa were recovered, with genus-level designation attributed to approximately 80% of the total taxa found (Table 9). The most diverse communities (as measured by richness) were found in the forest interior and the least diverse were found in the center of the slash piles (Table 10). Richness was also higher at the sampling depth of 20 cm compared with 5 cm below the forest floor. Overall, the most abundant genera were *Bradyrhizobium*, *Gemmatimonas*, *Alicyclobacillus*, *Afipia*, *Steroidobacter*, *Spartobacteria*, and subgroups Gp1, Gp2, Gp3, and Gp6 from the Acidobacteria.

Table 9. Number of taxa designated to each level of taxonomic classification as determined by double-barcoded 16S amplicon sequencing.

	V1V3	**V4V5**
Overall	863	833
Domain	2	2
Phylum	10	11
Class	19	18
Order	36	36
Family	112	110
Genus	684	656

Table 10. Taxonomic richness as determined by double-barcoded 16S amplicon sequencing.

	V1V3	**V4V5**
Overall	863	833
Pile 1	661	606
Pile 2	716	667
Pile 3	705	700
5 cm	729	693
20 cm	791	756
Forest	674	634
Edge of forest	615	584
4.5 ft	643	602
15 ft	625	618
Center	577 (piles 2 and 3 only)	557 (piles 2 and 3 only)

IV. Management implications

Numerous soil quality guidelines for National Forest Systems, industry, or private land specify limits of detrimental soil impacts at 20% of the harvest unit (Page-Dumroese et al. 2010). These limits are meant to help maintain forest soil productivity during and after harvesting or biomass thinning operations. Fire suppression activities has shifted forest stand structure resulting in more destructive wildfires and therefore more restoration programs are focusing on thinning (Jiménez-Esquilín et al. 2007). Thinning operations create large amounts of slash material that is usually disposed of by piling and burning resulting in soil heating and concomitant changes in soil physical, chemical, and biological properties. Our data show that soil texture and season of burning are both important factors to consider when planning slash pile burning operations. Many soil scientists and land managers are interested in maintaining soil productivity after harvesting and in the soil post-fire changes associated with slash pile burning. Thus, our results on the importance of soil texture and moisture will be of interest to many land managers.

This collaborative effort results in a wide applicability for our study results. We note that fine- and coarse-textured soils do not respond similarly to slash pile burning. The magnitude and extent of statistically significant changes in soil chemical changes indicates the need to address the season of burning. We note that soil chemistry had not returned to pre-burn levels after 2 years. In addition, the shift of microbes within the burn scar is likely one cause for differences in plant reestablishment on older burn scars.

We observed a rapid change in soil nutrient bioavailability which had not returned to pre-burn conditions at the end of this study. Alteration of soil properties important to soil processes may negatively impact forest ecosystems at localized scales.

One question that was asked at the outset of this effort was if there was a significant difference between upward facing and forward facing energy sensors. These data indicate that there are differences, but not always. We maintain that forward facing sensors probably most closely mimic the energy load received by a ground surface covered with rough needles, twigs, or other organic matter. Future efforts should consider installing thermocouple arrays over the pile to capture temperature distribution in the flames and plume above the pile. It would also be informative to install and downward facing heat sensor over the pile to capture the upward directed energy release. The data captured here indicate that heating of soil outside the perimeter of the pile is likely minimal and, at best, is limited to 1 m around the pile perimeter. This might change if all organic material was removed resulting in enhanced heating of the mineral soil since the organic horizons act as an insulative blanket over the mineral soil.

The collaboration, publications, presentations, and on-going monitoring of soil changes over time are important to sustainably managing forest residues from thinning or bioenergy harvest operations. Our data will inform managers about the risks and benefits of slash pile burning and help determine the appropriate season for ignition.

V. Relationship to other recent findings and ongoing work

This JFSP project has strong support from land managers throughout the Intermountain west, particularly with soil scientists working to maintain soil productivity after harvest and site preparation activities. Members of the research team are involved in a number of on-going efforts that build from this research project:

- **Heat movement into the mineral soil.** Study sites such as ours provided ideal data for evaluating both short- and longer-term impacts on soil physical, chemical, and biological properties. The effects of burning on returning vegetation are being monitored. One more year of field sampling will help provide more conclusive results and complement our existing data.
- **Standard wood stake decomposition was started on all study sites and sample collection will continue to help determine alterations in soil biology due to slash pile burning.** Preliminary results from all sites suggest that increased soil temperature, particularly during fall burning, likely alters belowground fungal components. We will continue to collect our wood stakes for 2-3(depending on the site) more sample dates to determine the trajectory of decomposition over time. We will then be able to analyze this data in the context of our world-wide set of decomposition data with standard wood stakes to determine how slash piles differ from prescribed broadcast burns or wildfires.

VI. Future Work Needed

As we originally proposed, we have completed four years (three years funded by JFSP and one year extension) worth of data collection to determine heat movement into the soil during slash pile burning on fine- and coarse-textured soil during spring and fall burn seasons. We examined the effect of those burns on soil physical, chemical, and biological properties. We have drawn significant conclusions about the impact of burn season and soil texture on soil responses. However, our data have the potential to be much stronger if we are able to (1) devise a long-term monitoring plan for these sites to determine vegetation regrowth responses, (2) determine more definitively the microbial species shift after burning using next-generation techniques such as metagenomics, (3) measure the upward release of energy, and (4) measure soil heat changes outside the pile with and without organic horizons. Understanding the degree, extent, and duration of belowground chemical and biological changes are not well documented and additional data would help land managers understand the risks and benefits of pile burning.

VII. Deliverables

All proposed products are complete, unless otherwise stated as *in review* or *in preparation* at the end of the citation.

Proposed	Delivered/Status
Annual progress reports RJVA's	• Progress reports were completed each year through 2013 • Annual reports for the RJVA between the USDA Forest Service and both Michigan Technological University and the University of Idaho
Final JFSP project report	• Final report: Below-ground Impacts of Pile Burning in the Inland Northwestern U.S (JFSP #11-1-8-2)
Data collection	
We proposed to collect soil temperature and samples to examine changes in soil physical, chemical, and biological properties. With a one-year extension we were able to collect post-fire data for 2-3 years, depending on the site.	• We installed 4 burn pile sites at the Lubrecht Experimental Forest, 1 burn pile site at the Priest River Experimental Forest, and 3 burn pile sites at the Pringle Falls Experimental Forest. Pre- and post-burn soil characterization data were collected. • Thermocouples were placed in 1 burn pile and in unburned soil at least 2 weeks prior to burning. Thermocouples were placed at 3 locations in under the pile (to a depth of 50 cm) and radiating outside the pile (1, 2, 3, and 5 m out and to a depth of 30 cm). • Standard wood stakes were installed shortly after burning to determine changes in decomposition rates.
We proposed to collect data from 35 year-old slash pile scars on the Flathead National Forest.	• We installed 3 replicate plots in old burn piles on the Flathead National Forest and collected soil samples from inside and outside the burn piles to characterize soil conditions. • Standard wood stakes were installed inside and outside the burn scars to determine if microbes responsible for decomposition are different.
Manager's workshops	
We proposed to conduct a field tour at each site.	• We participated in a field trip with school children from the Priest River School District to discuss how slash piles may alter soil properties (in September 2012, 2013, and 2014). • We participated in field tours at all our sites with land managers and students from local Universities to discuss harvesting, site preparation, and soil disturbance.
We proposed to conduct workshops with	• **Presentation:** met with soil scientists, silviculturists, and hydrologists to discuss preliminary results at the Region 1 soil and hydrology meeting. Meeting on Oct 11, 2012 and March

interested forest managers in Region 1 and 6.	13, 2013. • "Soil disturbance, slash piles, and long-term productivity" **presented** in Ecosystem Processes course taught at the University of Idaho, Moscow, ID (in March 2012, 2013, and 2014) to undergraduate students. • "Soil disturbance, slash piles, and maintaining soil productivity" **presented** in Silviculture course taught at the University of Montana, Missoula, MT (in April 2013 and 2014) to undergraduate students.
Technology transfer at meetings and trainings We were invited to present our research results at a variety of meetings. We also offered presentations and posters at national and international venues. We provided recommendations and insights based on our latest results. There was significant interest from soil scientists and others who routinely burn piles in an effort to dispose of excess slash.	• "Modeling soil heating and moisture transport under extreme conditions: Forest fires and slash pile burns" **presented** at the USDA FS Missoula Fire Lab Seminars, Missoula, MT Oct 2011. • "Soil heating and evaporation under extreme conditions: Forest fires and slash pile burns" **presented** at the AGU Fall Meeting, San Francisco, CA, Dec. 2011 (Published abstract) • "Modeling soil heating and moisture transport under extreme conditions: Forest fires and slash pile burns" **presented** at the AMS 30th Conference on Agricultural and Forest Meteorology, Boston, MA • "Soil disturbance and productivity changes associated with timber harvesting" **presented** at the Family Forester Workshop, Jan 18, 2013. • "Mineralogical and micromorphological modifications in soil affected by slash pile burn" **presented** at the ASA, CSSA and SSSA Annual Meetings, Tampa, FL 2013. • "How much woody biomass should I leave after harvesting and site preparation?" **presented** at the Inland Empire Reforestation Council, Mar 4, 2014 • "Forest dynamics after thinning and fuel reduction at Pringle Falls Experimental Forest" **poster presented** at the Society of American Foresters annual meeting, Oct. 2014. • "A non-equilibrium model for soil heating and evaporation under extreme conditions" **presented** at the AMS 31st Conference on Agricultural and Forest Meteorology, Portland, OR, November 2014. • "Belowground impacts of pile burning in the Inland Northwest, USA" **presented** at the 7th International Conference on Forest Fire Research, Coimbra Portugal, Nov. 2014 (Published extended abstract). • Mineralogical and micromorphological modifications in soil affected by slash pile burn **presented** at the 7th International Conference on Forest Fire Research, Coimbra Portugal, Nov. 2014 (Published extended abstract). • Transport of CO_2 and other combustion products in soils during slash-pile burns **presented** at the 7th International Conference on Forest Fire Research, Coimbra Portugal, Nov. 2014 (Published extended abstract).

Refereed publications – 4 were promised in the original proposal one has been accepted and 3 others are in preparation with the addition of 4th year data.	
1. Temperature profiles	• Massman, WJ. 2012. Modeling soil heating and moisture transport under extreme conditions: Forest fires and slash pile burns. Water Resources Research 48: W10548, doi:10.1029/2011WR011710 • Kirby, EA, WJ Massman, and KM Smits. 2014. The effect of fire on the thermal properties of a forest soil. ***In preparation*** *for publication* • Massman, W.J. 2015. A non-equilibrium model for soil heating and moisture transport during extreme surface heating. Geoscientific Model Development. ***In press.***
2. Wood decomposition	• Page-Dumroese, D.S., Jurgensen, M.F., Keyes, C., Tirocke, J.M. Alteration of wood decomposition rates after slash pile burning in the Inland Northwest. ***In preparation*** *for submission to Fire Ecology in 2015.*
3. Soil Changes	• Page-Dumroese, D.S., Jurgensen, M.F., Tirocke, J.M. 2015. Mineral soil changes associated with slash pile burning season. ***In preparation*** *for submission to the Soil Science Society of America Journal in 2015*

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