Effects of burning hand-piled slash

Alexander M. Evans[A,D], Clinton S. Wright[B], and Karen A. Haubensak[C]

[A]The Forest Guild, 2019 Galisteo Street, Suite N7, Santa Fe, NM 87505, USA.

[C]USDA Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, 400 North 34th Street, Suite 201, Seattle, WA 98103, USA.

[C]Northern Arizona University, Department of Biological Sciences & Merriam-Powell Center for Environmental Research, 617 S. Beaver Street, Flagstaff, AZ 86011-5640, USA.

[D]Corresponding author. Email: zander@forestguild.org

Abstract.

Each year in the western United States, tens of thousands of hectares of slash from forest thinning is burn in piles. Pile burning can affect soils, vegetation, and overstory trees. This study uses a rigorous experimental framework with study sties in Washington and New Mexico to better understand the effect of pile burning. Thermocouple measurements show that for the 1.2 m high piles soil heating was intense and long. Maximum temperatures were well above 400°C and temperatures above 60°C lasted for many hours. Flame heights averaged 3.7 m and 5.3 m for the Washington and New Mexico sites respectively and were reduced by increased moisture. Vegetation survey showed no difference between piles burned one and three years ago. The lack of significant differences between vegetation survey of piles of different ages suggests that vegetation recovery requires a longer term study to measure. Invasive species were present pre-post-treatment on both sites, but long-term monitoring will be necessary to gauge their impact.

Additional keywords: ponderosa pine, fuel treatment, vegetation recovery, soil heating

Introduction

Millions of acres of fuels reduction treatments are being implemented each year in an effort to mitigate the threat of wildfire at the wildland-urban interface. Federal land management agencies alone treated fuels on 21.3 million acres between 2008-2012 (Bracmort 2013). Typical hazardous fuel reduction treatments target small diameter trees for removal producing large amounts of unmerchantable woody material and elevating surface fuel loadings (Agee et al. 2000, Fulé et al. 2002, Hjerpe et al. 2009). Thinning without treating the slash created by the thinning can result in fire behavior that is more extreme than in untreated areas (Stephens 1998, Innes et al. 2006). Hence, mitigating the increased fuel generated by thinning is an important management consideration. Currently, there are few commercial markets for this woody material, so it is commonly piled by hand or with heavy machinery and burned on site (Farnsworth et al. 2003, Fulé et al. 2004, Seymour and Tecle 2005, Evans and Finkral 2009). Data from the National Fire Plan Operations and Reporting System (NFPORS) indicates that the USDA Forest Service alone created more than 25,000 hectares of piles in the western United States during 2014.

Pile burning concentrates fuels and hence fire effects. In forests adapted to low or moderate intensity fires, pile burning may create conditions such as soil temperatures and flame heights that may cause vegetation and soil impacts managers want to avoid. For example, soil heating from slash pile burning in thinned stands can reduce rates of reestablishment by native understory plant species and enhance rates of exotic plant invasion (Dickinson and Kirkpatrick 1987, Wolfson et al. 2005, Zouhar et al. 2008, Owen et al. 2009, Fornwalt and Rhoades 2011). In one case pile burning contributed to poor regeneration for half a century within pile burn scars (Rhoades and Fornwalt 2015).

The effects of pile burning are influenced by a wide range of factors including pile size, fuel moisture, and soil saturation. Wright and colleagues (2010) demonstrated that pile size, shape, age, species composition, packing ratio have a significant effect on pile biomass and emissions estimates. Previous studies have indicated that heat pulse from slash piles was determined by fuel composition, not on pile size (Busse et al. 2013). No surprisingly, the greatest heat tends to be in pile centers and soil heating declines sharply at pile edges (Busse et al. 2013). Frandsen and Ryan (1986) demonstrated that saturated soils reduced soil temperatures under a burning piles.

We designed this study to understand the effects burning hand piles has on vegetation, soils, and overstory trees. We present data to answer three broad questions. First, how are pile characteristics related to the duration and depth of soil heating? Second, how is vegetation recovery influenced by pile characteristics? Third, what effects do pile characteristic have on flame heights and damage to overstory? Our hope is that by answering these questions we can help forest managers understand potential impacts of pile burning and to adjust pile burning plans to minimize unwanted effects.

Methods

Study area

We established two to three hectare study sites on land managed by by the Naches Ranger District of the Okanogan-Wenatchee National Forest in central Washington (hereafter WA) and Santa Clara Pueblo in north-central New Mexico (hereafter NM). Both sites were in dry conifer forests that had been recently thinned of small diameter (<20 cm d.b.h.) trees to reduce stand density.

The NM site was located on relatively flat ground at 2400 m elevation 20 km west of Española, New Mexico in the Jemez Mountains (N 36°00’56.4”; W -106° 16’59.9”). The area is characterized by warm summers (summer maximum temperatures average 32°C) and cold winters (winter minimum temperatures average -14°C) with an overall average temperate of 10°C . The area gets between 26 and 38 cm of precipitation with much of it coming in the summer and fall during the monsoon period based on the Santa Clara Canyon RAWS station. Soils are well drained Totavi gravelly loam. The site is in a mature ponderosa pine (*Pinus ponderosa*) stand with a sparsely vegetated understory dominated by blue grama (*Bouteloua gracilis*), june grass (*Koeleria cristata*), and awnless brome (*Bromus inermis*). The stand was thinned in 2011 to a basal area of 19 m^2 ha^{-1}; thinning debris (branches and tops only) was piled by hand at a density of 50 piles ha^{-1}.

The WA site was located on gently sloping terrain (5-15 percent slope, easterly aspect) at 1,130 m elevation, above Rimrock Lake in the eastern Cascade Range (N 46°39’27”; W 121°09’26.8”). Soils are well drained McDanielake ashy sandy loam. The understory dominated by herbaceous species, including elk sedge (*Carex geyeri*), pine grass (*Calamagrostis rubescens*), Idaho fescue (*Festuca idahoensis*), and Virginia strawberry (*Fragaria virginiana*), with scattered low shrubs, including kinnikinnick (*Arctostaphylos uva-ursi*) and grouse whortleberry (*Vaccinium scoparium*). The site is in a mixed conifer stand comprised of a mixture of ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), and grand fir (*Abies grandis*). The stand was made up of many small trees between 15 and 30 cm d.b.h. with scattered old ponderosa pines and western larches greater than 60 cm d.b.h. The stand was thinned in 2011 to a basal area of 13 m^2 ha^{-1}; thinning debris was piled by hand at a density of 90 piles ha^{-1}.

Study design

This study used a blocked factorial design with replication. The WA and NM sites were the two blocks. For each site we burned five fall-built piles in the fall of 2011, 2012, and 2013; five fall-built piles in the spring 2012 and 2013; five spring-built piles in the spring of 2012, 2013, and 2014; and five spring-built piles in the fall of 2012 and 2013. The five pile ages for two burning seasons were each replicated five times for a total of 100 piles. Immediately before the first fall and spring burning period, we built 25 hand piles of equal size at each location; five replicates from each build period were burned each season at each location for two years following building to achieve a fully crossed experimental design.

At each site 50 pile locations were established in accordance with standard practice for the area, i.e., their location was not random, but designed to minimize damage to residual trees and the risk of fire spread from one pile to another. Before building the piles, we assessed vegetation coverage by species three 0.5 × 0.5 m subplots at each pile. The center of the interior edge of subplots 1 and 2 were 0.25 m upslope and downslope of the pile marker, respectively. The center of the interior edge of subplot 3 was located 0.5 m from the pile marker to the left of plot center. Vegetation coverage by species was reassessed in the same permanently marked subplots. An additional set of 12 0.25 m^2 plots were placed in a transect across the NM site to enable comparison between unburned areas and pile footprints. Also before pile were built, we installed an array of 16 type-K thermocouples into undisturbed soil beneath the pile at four depths (0, 5, 15, 30 cm depth) and four distances from the pile center (0.2, 0.7, 1.2, and 1.5 m). We took soil samples from undisturbed ground within the pile perimeter. We measured the distance and azimuth to the nearest live tree greater than 10 cm in each quadrant (NE, NW, SE, SW) and recorded its species, height, height to crown base, height to live crown, and diameter at breast height.

Piles were composed of coniferous thinning debris and sized to reflect typical hand piling specifications (half spheres with a 1.2 m radius, 1.2 m tall). Piles at the NM site were composed of <7.6 cm diameter woody material only (branches and small tops), as the area had been made available for firewood collection prior to piling. In contrast, the piles at the WA site included tops, branches, and 1.5-2 m long pieces of bole wood up to approximately 20 cm in diameter. The material in each pile was weighed during the pile-building process with hanging scales; pile weight measurements were corrected to a dry weight basis by collecting representative moisture content subsamples for each pile.

Piles were burned during the typical spring and fall burning windows at each location. Piles were ignited with a drip torch approximately every 15-20 minutes. The entirety of the ignition period typically extended over a 1.5-3 hour window of time. Technicians monitoring the piles allowed them to burn unmanipulated until they self-extinguished. They did not add fuel to the piles with the exception of logs that rolled off the pile in Naches which they moved back onto the main fire.

We timed the duration of flaming, smoldering, and total combustion for each pile (flaming, smoldering, total burn-out times). We also visually estimated flame height every 1-3 minutes for the first 20 minutes following ignition and periodically thereafter until the end of flaming; a 3-m long, graduated measuring pole was positioned adjacent to each pile for scale. We measured the surface and below ground temperature every 10 seconds during pile burning with the array of 16 type-K thermocouples.

Upon completion of all combustion (i.e., out cold), we collected all residual material in two 0.60 m^2 wedge-shaped areas within the pile perimeter. Pure charcoal fragments were separated from unburned and charred wood. Then we oven dried all material at 100°C for a minimum of 48 hours and weighed on a precision balance to determine oven-dry mass of both constituents. At the end of the study in 2015, we reassessed vegetation subplots, overstory condition, and soils.

Results

Soil

Piles at the WA site reached a maxim temperature of 879°C and the average of maximum temperatures across the 30 measures at 20 cm horizontally from the pile center was 595°C (SD 154). Below the surface, temperatures were moderated and in WA the maximum temperature 5 cm below the surface was 211°C. At the NM site, temperatures at 20 cm horizontally from the center of the pile at the soil surface reached 916°C and on average, the maximum temperature was 488°C (SD 223). The maximum temperature 5 cm below the surface was 202°C.

The duration of heating can be as important as the maximum temperature. We used a cut off of 60°C as a temperature which can kill plant tissue at a duration of one minute (Agee 1993 p. 114). Piles burned longer on average at the WA site than at the NM site (p = 0.008) (Fig 1). At 15 cm below the surface and deeper, the soil heating was brief or non-existent. Thermocouples only record temperatures above 60°C at 15 cm below the surface at 3 piles in WA and 2 piles in NM. Thermocouples at 30cm below the surface did not measure any heating above 60°C during the pile burning.

At both sites, the heat from pile burning was concentrated at the center of the pile. On average, soil temperatures at the surface and horizontally 0.7 m from the pile center were only above 60°C for 31 minutes at the WA site and 8 minutes at the NM (Fig. 3). At 1.2 m and 1.4 m horizontally from the pile center, increased temperatures from pile burning were brief at the surface (Figure 2). At 1.2 m and 1.4 m horizontally from the pile center, pile burning did not raise soil temperatures above 60°C even at the soil surface.

Burning consumed a large proportion of the piled material: about 94% at both sites. The remaining material included about 1% charcoal and 5% wood for the WA piles and 3.5% charcoal and 2.5% wood for the NM piles. In other words, pile burning added 2.5 kg (SD 0.8) and 3.1 kg (SD 2.4) of charcoal per pile in WA and NM respectively. On a per hectare basis, this results in the addition of 220 kg or 150 kg of charcoal to the WA and NM sites respectively.

Vegetation

In 2011 when the project started, there was an average of 56% (SD 26) vegetation cover on in WA and 21% (SD 15) vegetation cover in NM. When the project started, there was an average of 4.7 species per subplot (SD 1.5) in WA and 3.3 per subplot (SD 1.6) in NM. In WA pre-treatment, the majority of the ground was strawberry (*Fragaria virginiana*) or Idaho fescue (*Festuca idahoensis*) with elk sedge (*Carex geyeri*) and 29 other species making up the rest of the ground cover. Pinegrass (*Calamagrostis rubescens*) and twinflower (*Linnaea borealis*) covered a large proportion of the ground on a few subplots, but were less common across the stand. Post-treatment Idaho fescue remained the most species based on average ground coverage, strawberry and elk sedge declined in importance and tiny trumpet (*Collomia linearis*) increased in importance. The same total number of species were identified post-treatment (32 species), though some such as kinnikinnick (*Arctostaphylos uva-ursi*) were identified pre-treatment and not post treatment and others such as tiny trumpet were not identified pre-treatment.

In NM pre-treatment, Small-leaf pussytoes (*Antennaria parvifolia*), blue grama (*Bouteloua gracilis*), june grass (*Koeleria cristata*), and fetid goosefoot (*Chenopodium graveolens*) provided the most ground cover though 29 different species were identified in the subplots. Post-treatment, june grass and blue grama remained important, but golden aster (*Chrysopsis villosa*) provided more cover than small-leaf pussytoes or fetid goosefoot. The 28 species identified across all subplots post-treatment.

On the WA site, two invasive species were present: bull thistle (*Cirsium vulgare*) and dandelion (*Taraxacum officinale*). No bull thistle was found pre-treatment on any of the subplots, but post treatment it had invaded 13 subplots and had an average coverage of 0.23% (SD 1.0). Looking only at the 13 subplots with bullthistle, post treatment the average coverage was 2.6% (SD 2.5). The number of subplots with dandelion increased from 21 to 28 and the average coverage changed from 0.53 (SD 2.12) pre-treatment to 0.24 (SD = 0.56) but the decrease was not statistically significant at the 0.05 level. On the NM site, an invasive species, cheat grass (*Bromas tectorum),* was found on 8 subplots pre-treatment and 12 sub-plots post-treatment. On average cheat grass made up 3.8% (SD 3.9) of the ground cover pretreatment and 3.5% (SD 2.6) post-treatment.

In 2015 post-treatment, there was an average of 11% (SD 14) and 5% (SD 6) vegetation cover on subplots in WA and NM respectively. Post burn there was an average of 3.2 species per subplot (SD 1.3) in WA and 1.5 (SD 1.4) in NM. In WA, 99% of plots declined in vegetation coverage post-treatment and 85% of plots declined in vegetative coverage in NM. In 2015, we measured an additional series of 12 $0.5m^2$ plots across the site (outside of piles footprints) and on these control plots vegetation covered an average of 29% of the ground. The control plots had significantly greater coverage than the pile plots (p = 0.009).

There was no significant difference at the WA or the NM site in the vegetative coverage between those piles that had the most time to recover from burning before the final sampling in summer 2015 (i.e., those burned in 2011 and spring 2012) and those that had the least time to recover (i.e., those burned in fall 2013 and spring 2014). However, looking solely at the third subplot in WA, which was 50cm from pile center (subplots 1 and 2 where 25 cm from the pile center) there is an increase in post burn vegetation. On the WA site, the third subplots of piles that had the most time to recover had a significantly higher mean (16%; SD 13) than those burned more recently (3.2% SD 2.9). The NM third subplots burned earlier were not significantly different from those burned more recently. However, in NM, subplot 3 had significantly more vegetation coverage (6.8% SD 6.8) in 2015 than subplots 1 and 2 ($p > 0.003$) which had a mean of 3.7% (SD 5.2). Pre-treatment there was no significant difference between subplot 3 and subplots 1 and 2 in NM.

Overstory

The stands where our experimental piles burned were not unusual for the types of stands where managers often use pile burning as a treatment. Since both sites had been thinned, they were more open than untreated stands. Piles locations were selected to minimize interaction with remaining overstory trees. Overstory trees were an average distance of 7.1 m (SD 7.6; 6.9) from plot centers in both WA and NM (Fig 4a). The trees were smaller at the WA site where the mean DBH was 22 cm (SD 33) compared to 30 cm (SD 25) at the NM site (Fig. 4b). The basal area averaged 13 m^2/ha (SD 16) at the WA site and at NM was 19 m^2/ha (SD 13) (Fig. 4c).

On the WA site, maximum flame heights ranged from 1.8 to 6.1 m with a mean of 3.7 m (SD 1.2). Maximum flame heights were taller and occurred soon on the NM piles. The maximum flame heights in NM ranged from 3.7 to 8.5 m with an average of 5.3 m (SD 1.3). On average, piles in WA reached their maximum height in the first 8 minutes of ignition while piles in NM reached their maximum in the first 4.5 minutes of ignition. The moisture content of small branches on the day of burn was a significant predictor of flame height ($p < 0.001$; $R^2 = 55\%$). Not surprisingly, increased moisture reduced flame height (Fig. 5). Our post-burn survey of trees found minor bole scorch but no damage or change in tree health on either site.

Piles on the WA site had flaming combustion for an average of 95 minutes (SD 54) before transitioning to smoldering combustion. The NM piles had flaming combustion for significantly less time than WA piles ($p < 0.001$) with an average of 46 minutes (SD 19) before the transition to smoldering. The duration of flaming combustion varied with pile age (Fig. 6). At the NM site, the oldest piles burned for the longest time and there were significant differences between piles less than 2 years old and 2 year-old piles. Also, piles 1.5 years old took significantly longer to burn than piles less than 1 year old (Fig 6).

A linear model suggested that both pile age and pile weight on day of burn were significant predictors of flaming duration ($p > 0.001$; $R^2 = 34\%$) (Fig 7).

Discussion

Thermocouple measurements show that for the 1.2 m high piles soil heating was intense and long. Maximum temperatures were well above 400°C and temperatures above 60°C lasted for many hours. However, high temperatures and long duration only occurred in the top 15 cm of soil and only within about 1 m of the pile center. Although the built pile footprint was 1.2 m in radius and 1.2 m in height, the soil impact area was smaller. In the NM site, older piles burned longer which is likely due to the compression of fuels by snow and decomposition. Our results collaborate Busse and colleagues' (2013) results from piles burning in the Lake Tahoe Basin. They found that pile composition was a more important driver of soil heating than pile size. Piles with large pieces of wood generated heat about 100C for over 60 hours in some cases (Busse et al. 2013).

The lack of significant differences between piles that had 3 growing seasons to recover and those that had only one growing season to recover suggests that vegetation recovery requires a longer term study to measure. However, the vegetation response in the pile scars, particular at the edge of the pile scars, suggests the revegetation process is underway. In both WA and NM, subplot 3 appeared to revegetation more rapidly than subplots 1 and 2 which were 25 cm closer to the center of the pile. This may have been due to reduce duration of heating above 60°C, though on average subplot three received more than two hours of heating over 60°C at both sites. Other studies have found vegetation regrowth at pile edges and documented the impact of fire intensity on vegetation recovery (Dickinson and Kirkpatrick 1987, Fornwalt and Rhoades 2011). While in both WA and NM, the soil surface at 20 cm horizontally from the plot center experience many hours of heating above 60°C, but heating at 50 cm from the pile was likely a quarter to a half as long. Long term monitoring may help differentiate the small hand piles we assessed from the larger, machine built piles that can have long term negative impacts on tree regeneration (e.g., Rhoades and Fornwalt 2015).

The production of more than a half a kilogram of charcoal per m^2 over the 4.5 m^2 area of the built pile footprint may have helped with germination (Reyes et al. 2015). Briggs and colleagues (2012) showed that the addition of charcoal to the soil from ponderosa pine burning significantly increased the water-holding capacity and darkened the soil. An increase in water-holding capacity may have benefited plant growth, particularly in NM where moisture is often limiting.

Past studies have highlighted the risk of spread of invasive plants after pile burning (Wolfson et al. 2005, Zouhar et al. 2008). Our study did showed an increase in bull thistle on the WA site and continued presence of cheat grass. Bull thistle is a noxious weed that can inhibit the growth of ponderosa pine (Randall and Rejmánek 1993) while invasion of cheat grass can alter fire regimes (Davies and Nafus 2013). The WA site also had a continued presence of a less noxious invasive, dandelion, post-treatment. Longer term monitoring will be necessary to understand whether the small coverage of invasives plants recorded in this study expands. The degree to which pile scars are invaded is likely due to the prevalence of invasive plants in the surrounding stand and the size of burn scars. Both the WA and NM sites were relatively free from invasives, though the species found in the sampling existed throughout the stand. Mulching, scarifying, and seeding are effective tools for rehabilitating pile burn scars (Fornwalt and Rhoades 2011).

Using a conversion of charcoal to C of 78% based on measured C content of charcoal from similar piled fuels from Finkral and colleagues (2012), pile burning stored about 0.22 and 0.098 Mg of C ha^{-1} in the soils at the WA and NM sites respectively. Burning of larger slash piles can generate up to 0.34 Mg of C ha^{-1} (Finkral et al. 2012). This suggests that if all the piles reported for 2014 in the federal accomplishment database for the western US were burned, it would add between 2,450 and 8,500 M of C ha^{-1} to the soil.

Our study noted no significant damage to overstory trees. This is likely due to the relatively shallow depth of soil heating and the wide spacing of overstory trees relative to pile flame heights. Since the main mass of ponderosa pine roots extend down to 60 cm below the surface (Oliver and Ryker 1990), burning piles of similar magnitude to those in this study are unlikely to damage more than the top quarter of these roots. Maximum flames heights (3.7 m and 5.3 m on average for WA and NM) were shorter than the distance from pile center to nearest tree (7.1 m in both WA and NM) in the majority of cases. The minor scorch recorded was within the tolerance of ponderosa pine which can withstand 50 percent crown scorch (Oliver and Ryker 1990). Leaving piles on site for multiple years is likely to decrease flame heights but increase the duration of flaming combustion. Similarly, burning with higher fuel moistures will likely reduce the flame height from pile burning.

Conclusion

Overall, our study shows that controlled burning of hand pile fuels can have minimal impacts on ground story vegetation and overstory trees. We hope that our detailed measurements of pile characteristics and burn attributes provide managers with useful tools for planning fuel reduction treatments.

Acknowledgements

We would like to thank Jason Emhoff, Okanogan-Wenatchee National Forest and Daniel Denipah, Tom Naranjo, and the rest of the Santa Clara Pueblo Forestry Department for their assistance locating the study sites and facilitating burning. We acknowledge funding from the Joint Fire Science Program under project number JFSP-11-1-8-4.

References

Agee, J. K. 1993. *Fire Ecology of Pacific Northwest Forests*. Island Press, Washington, DC.

Agee, J. K., B. Bahro, M. A. Finney, P. N. Omi, D. B. Sapsis, et al. 2000. The use of shaded fuelbreaks in landscape fire management. *Forest Ecology and Management* 127(1-3):55-66.

Bracmort, K. 2013. *Wildfire management: federal funding and related statistics*. R43077, Congressional Research Service, Washington, DC.

Briggs, C., J. M. Breiner, and R. C. Graham. 2012. Physical and chemical properties of *Pinus ponderosa* charcoal: implications for soil modification. *Soil Science* 177(4):263-268 210.1097/SS.1090b1013e3182482784.

Busse, M. D., C. J. Shestak, and K. R. Hubbert. 2013. Soil heating during burning of forest slash piles and wood piles. *International Journal of Wildland Fire* 22(6):786-796.

Davies, K. W., and A. M. Nafus. 2013. Exotic annual grass invasion alters fuel amounts, continuity and moisture content. *International Journal of Wildland Fire* 22(3):353-358.

Dickinson, K., and J. Kirkpatrick. 1987. The Short-Term Effects of Clearfelling and Slash-Burning on the Richness, Diversity and Relative Abundance of Higher Plant Species in Two Types of Eucalypt Forest on Dolerite in Tasmania. *Australian Journal of Botany* 35(6):601-616.

Evans, A. M., and A. J. Finkral. 2009. From renewable energy to fire risk reduction: a synthesis of biomass harvesting and utilization case studies in US forests. *GCB Bioenergy* 1(3):211-219.

Farnsworth, A., P. Summerfelt, D. G. Neary, and T. Smith. 2003. Flagstaff's wildfire fuels treatments: prescriptions for community involvement and a source of bioenergy. *Biomass and Bioenergy* 24(4-5):269-276.

Finkral, A. J., A. M. Evans, C. D. Sorensen, and D. L. R. Affleck. 2012. Estimating consumption and remaining carbon in burned slash piles. *Canadian Journal of Forest Research* 42(9):1744-1749.

Fornwalt, P. J., and C. C. Rhoades. 2011. Rehabilitating slash pile burn scars in upper montane forests of the Colorado Front Range. *Natural Areas Journal* 31(2):177-182.

Frandsen, W. H., and K. C. Ryan. 1986. Soil moisture reduces belowground heat flux and soil temperatures under a burning fuel pile. *Canadian Journal of Forest Research* 16(2):244-248.

Fulé, P. Z., W. W. Covington, H. B. Smith, J. D. Springer, T. A. Heinlein, et al. 2002. Testing ecological restoration alternatives: Grand Canyon, Arizona. *Forest Ecology and Management* 170(1):19-41.

Fulé, P. Z., J. L. Jerman, and P. J. Gould. 2004. Slash compression treatment reduced tree mortality from prescribed fire in southwestern ponderosa pine. *Western Journal of Applied Forestry* 19(3):149-153.

Hjerpe, E., J. Abrams, and D. R. Becker. 2009. Socioeconomic barriers and the role of biomass utilization in southwestern ponderosa pine restoration. *Ecological Rest.* 27(2):169-177.

Innes, J. C., M. P. North, and N. Williamson. 2006. Effect of thinning and prescribed fire restoration treatments on woody debris and snag dynamics in a Sierran old-growth, mixed-conifer forest. *Canadian Journal of Forest Research* 36(12):3183-3193.

Oliver, W. W., and R. A. Ryker. 1990. Ponderosa pine. Pages 413-424 *in* R. M. Burns and B. H. Honkala, editors. *Silvics of North America*. Agriculture Handbook 654, USDA, Forest Service, Washington, DC.

Owen, S. M., C. H. Sieg, C. A. Gehring, and M. A. Bowker. 2009. Above- and belowground responses to tree thinning depend on the treatment of tree debris. *Forest Ecology and Management* 259(1):71-80.

Randall, J. M., and M. Rejmánek. 1993. Interference of bull thistle (*Cirsium vulgare*) with growth of ponderosa pine (*Pinus ponderosa*) seedlings in a forest plantation. *Canadian Journal of Forest Research* 23(8):1507-1513.

Reyes, O., J. Kaal, D. Arán, R. Gago, J. Bernal, et al. 2015. The effects of ash and black carbon (biochar) on germination of different tree species. *Fire Ecology and Society* 11(1):119-133.

Rhoades, C. C., and P. J. Fornwalt. 2015. Pile burning creates a fifty-year legacy of openings in regenerating lodgepole pine forests in Colorado. *Forest Ecology and Management* 336(0):203-209.

Seymour, G., and A. Tecle. 2005. Impact of slash pile size and burning on soil chemical characteristics in ponderosa pine forests. *Journal of the Arizona-Nevada Academy of Science* 38(1):6-20.

Stephens, S. L. 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behaviour in Sierra Nevada mixed-conifer forests. *Forest Ecology and Management* 105(21-35).

Wolfson, B. A. S., T. E. Kolb, C. H. Sieg, and K. M. Clancy. 2005. Effects of post-fire conditions on germination and seedling success of diffuse knapweed in northern Arizona. *Forest Ecology and Management* 216(1–3):342-358.

Wright, C. S., C. S. Balog, and J. W. Kelly. 2010. *Estimating volume, biomass, and potential emissions of hand-piled fuels*. GTR-PNW-805, USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Zouhar, K., J. K. Smith, and S. Sutherland. 2008. Effects of fire on nonnative invasive plants and invasibility of wildland ecosystems. Pages 7–45 *in* K. Zouhar, J. K. Smith, S. Sutherland, and M. L. Brooks, editors. *Wildland fire in ecosystems: Fire and nonnative invasive plants*. RMRS-GRT-42-vol. 6. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT.

Figures

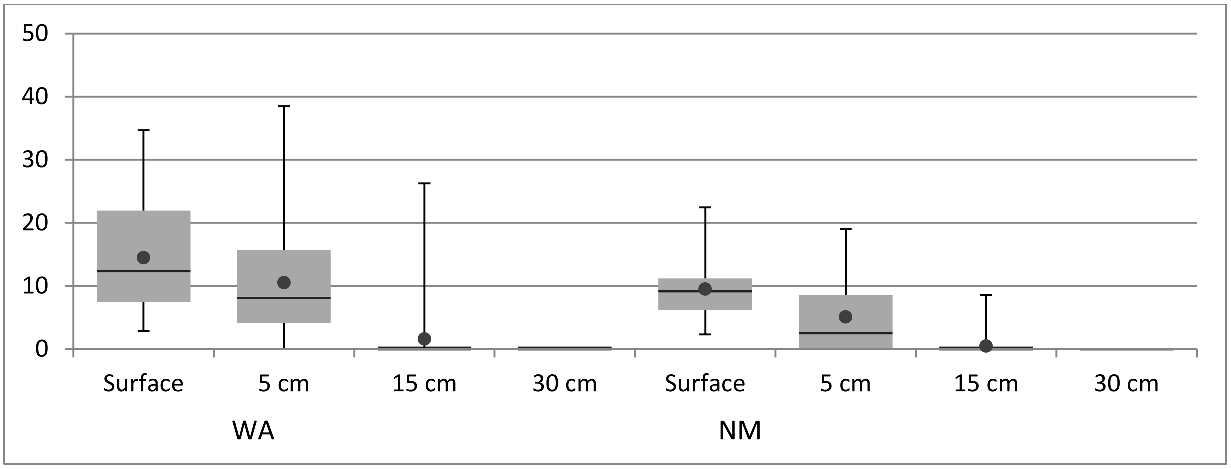

Figure 1 Duration of soil heating above 60°C at four depths, 20 cm horizontally from the pile center

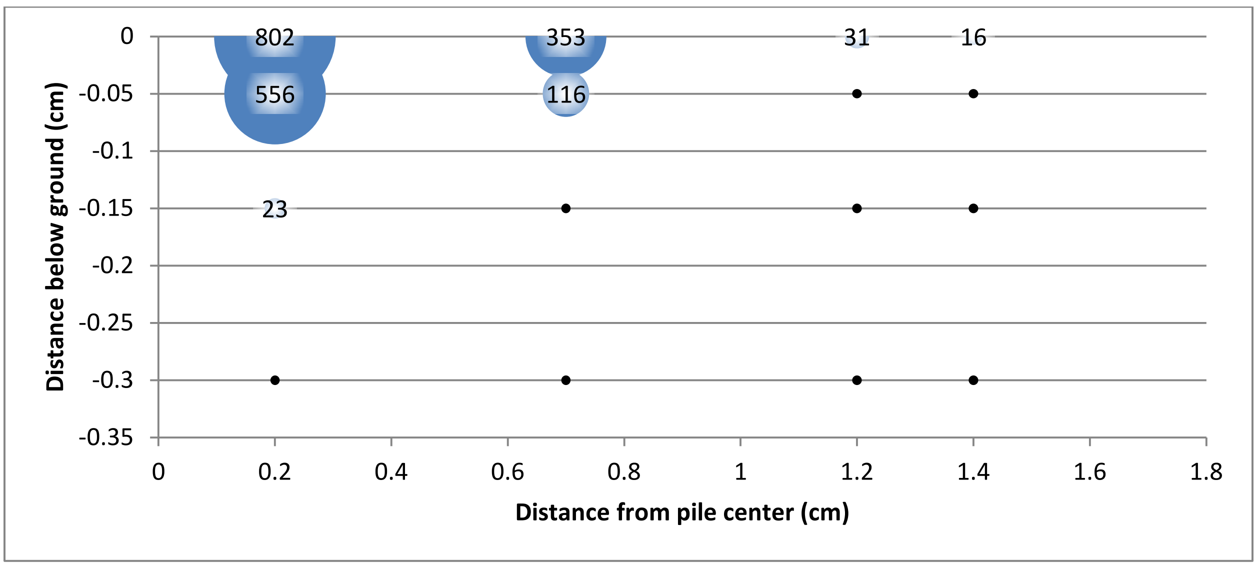

Figure 2 Average number of minutes above 60°C at each thermocouple location at the WA site.

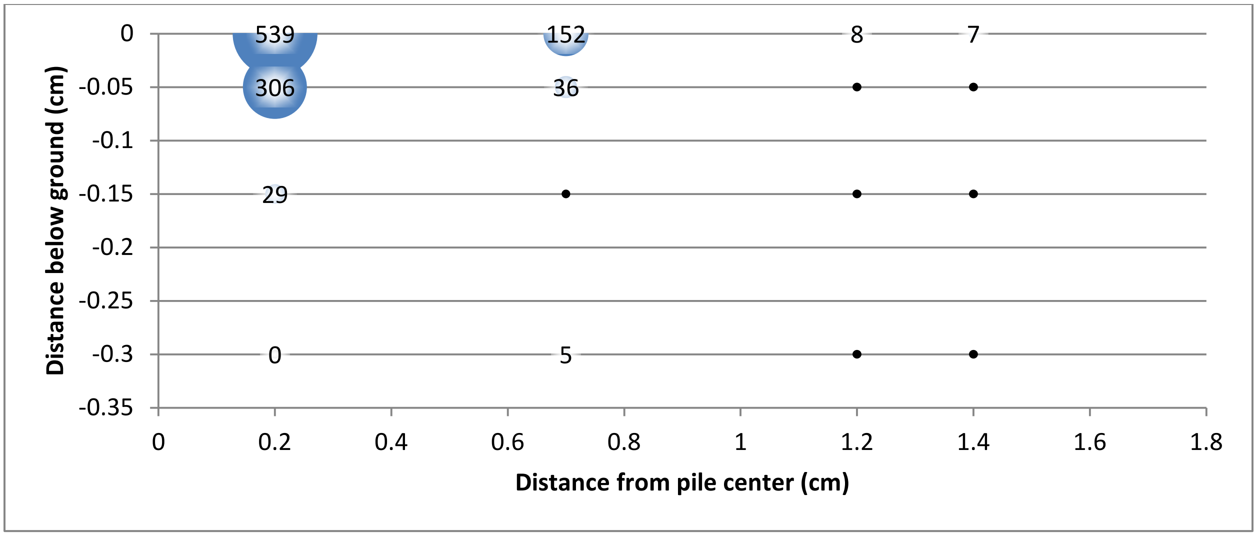

Figure 3 Average number of minutes above 60°C at each thermocouple location at the NM site.

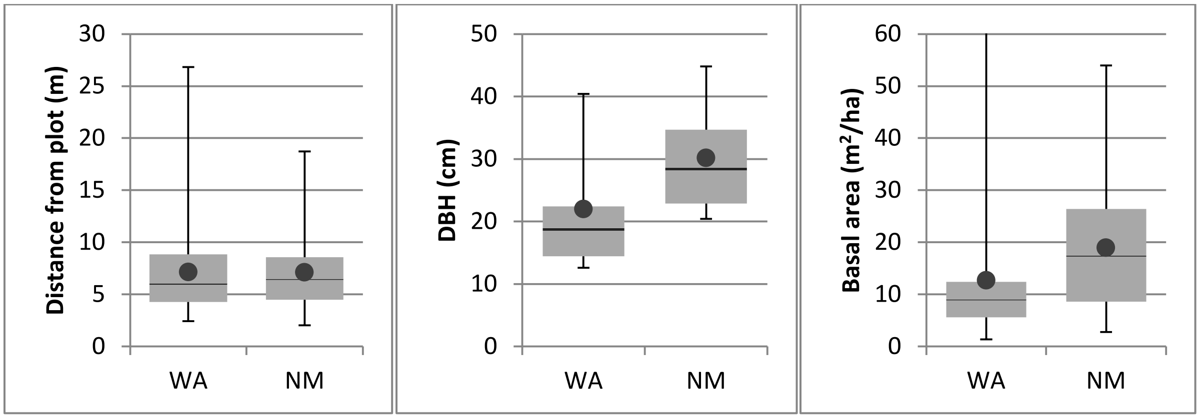

Figure 4a-c Box plots of a) distance from pile center to nearest tree b) diameter at breast height and c) basal area for each of the two study sites.

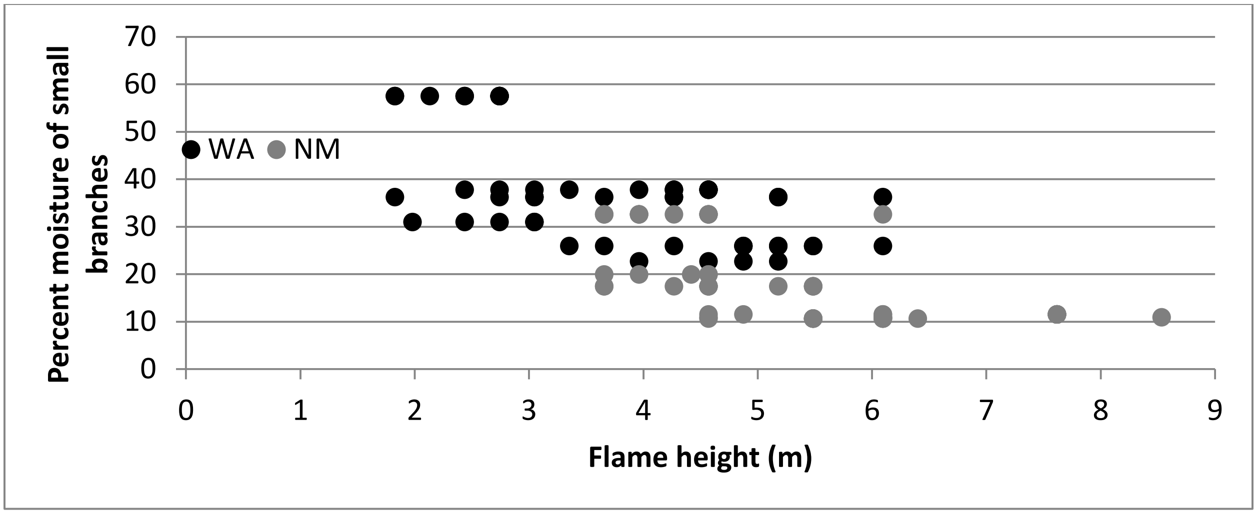

Figure 5. Percent moisture content of small branchs versus flame height

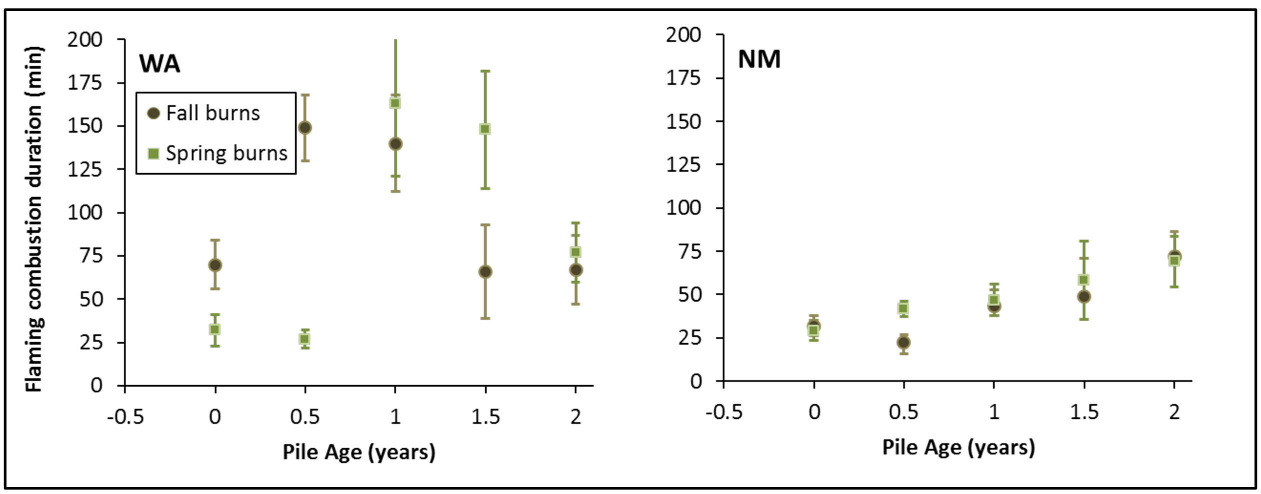

Figure 6. Duration of flaming combustion versus pile age by season of burn for each of the two study sites.

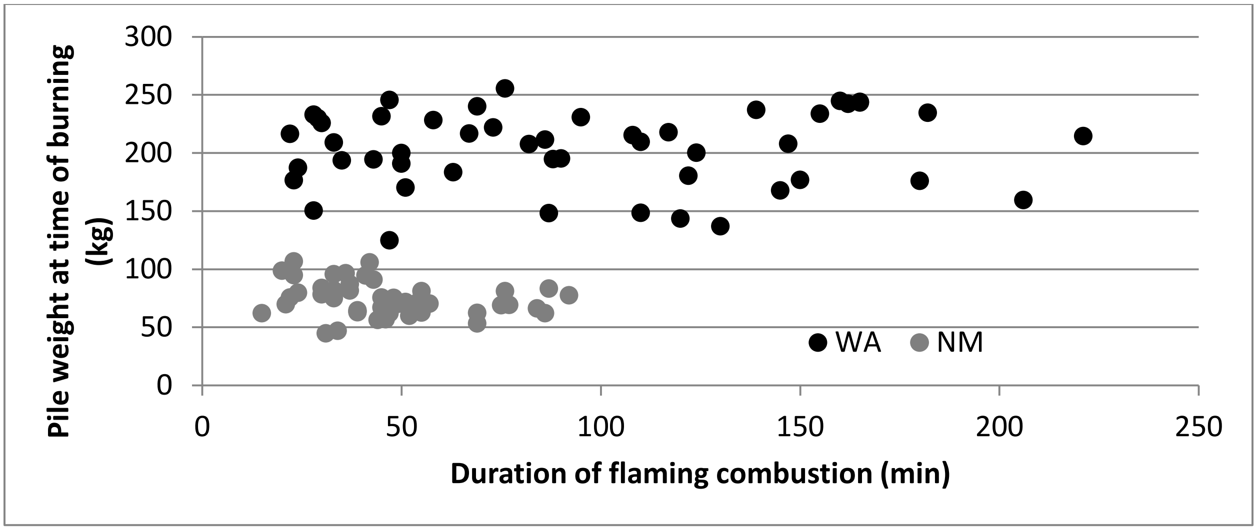

Figure 7. Pile weight at time of burning versus the duration of flaming combustion