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Pile age and burn season influence fuelbed properties, combustion dynamics, fuel consumption, and charcoal formation when burning hand piles

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ABSTRACT

Piling and burning is widely used to dispose of unmerchantable debris resulting from thinning in forests throughout the western United States. Quite often more piles are created than are burned in a given year, however, causing piles to persist, accumulate, and age on the landscape. The effects of burning piles of increasing age has not been studied. We examined the effects of time since construction (i.e., pile age, in roughly six month increments for two years) and burn season (fall and spring) on fuelbed properties, combustion dynamics, fuel consumption, and charcoal formation for hand-constructed piles in thinned ponderosa pine-dominated sites in New Mexico (n = 50 piles) and Washington (n = 49 piles). Piles compacted over time similarly for both study sites, losing approximately 15% of their height annually for the first two years following piling. Peak flame height decreased and the duration of flaming combustion increased with increasing pile age for both burn seasons in New Mexico, yet depended on burn season in Washington. Increasing fuel moisture and compaction reduced peak flame height and increased flaming duration modestly for both sites. Peak flame height was reduced 6–7 cm and flaming duration increased 0.9–2.3 min for every percentage increase in small fuel moisture. Similarly, peak flame height was reduced 4–5 cm and flaming duration increased 0.6–0.8 min for every percentage reduction in pile height. Fuel consumption was high, averaging 90% in New Mexico and 95% in Washington. Fuel consumption patterns differed between locations, however; fuel consumption decreased with age and was slightly higher for spring than fall burns in New Mexico, whereas, neither pile age nor burn season affected fuel consumption in Washington. Charcoal formation as a fraction of pre-burn pile weight averaged 2.8% in New Mexico and 1.2% in Washington, and was not affected by pile age or burn season. Fuel consumption and charcoal production were unaffected by fuel moisture or compaction levels at either site. Findings from this study will inform fuel and fire managers about the potential effects on fire behavior, fuel consumption, and charcoal formation of burning piles of different age in different seasons under different environmental conditions.

1. Introduction

Some dry, conifer-dominated forests in the western United States (U.S.) are at risk of uncharacteristically intense, stand-replacing wildfires (e.g., Fulé et al., 2004; Noss et al., 2006). In many areas, a century of fire suppression, intensive grazing, and logging have created forests that are overstocked with small diameter trees (Covington and Moore, 1994; Keane et al., 2002). Coupled with this overstocking, projected increases in wildfire activity associated with predicted future climate in many western landscapes (McKenzie et al., 2004, Littell et al., 2009), suggest the need to modify forest structure and composition, and to treat hazardous fuels in order to maintain or restore resilient, sustainable forests and fire regimes in dry forest types (Brown et al., 2004; Agee and Skinner 2005; Agee and Lolley 2006; Stephens et al., 2013). To that end, large numbers of fuel treatments are being implemented each year in the U.S.; federal land management agencies treated fuels on an average of 1.6 million ha annually nationwide from 2001 to 2017 (DOI and USFS, 2008, 2017).

Typical hazardous fuel reduction treatments target small diameter trees for removal producing large amounts of unmerchantable woody

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material and elevating surface fuel loadings (Agee et al., 2000; Fulé et al., 2002; Hjerpe et al., 2009). Elevated fuel levels associated with many thinning treatments make disposal through broadcast prescribed burning difficult or impossible owing to a variety of factors, including the potential for high mortality among residual trees, the possibility of smoke incursions into adjacent communities, and the risk of escape associated with potentially high fire intensity. As there are currently few markets for this material, it is commonly piled by hand or with heavy machinery and burned on site (Evans and Finkral 2009; Han et al., 2010). The U.S. Forest Service alone piled and burned on average over 33,600 ha annually from 2005 to 2014, mostly in the western U.S., according to the National Fire Plan Operations and Reporting System. For a variety of reasons (e.g., lack of favorable weather conditions, funding or staffing shortages, air quality restrictions), it is not uncommon for more piles to be created than can be burned in many locations causing piles to accumulate on the landscape; in some cases these unburned piles burn in unplanned wildfires (Evans and Wright, 2017).

Because of concerns about smoke and air quality from prescribed fires, including pile burning, managers must understand and be able to accurately estimate fuel consumption and emissions. All biomass burning releases carbon dioxide (CO_2) and other pollutants into the atmosphere and converts woody fuels to charcoal and pyrolized soil organic matter (pSOM) when combustion is incomplete (González-Pérez et al., 2004), affecting total ecosystem carbon pools and fluxes (Forbes et al., 2006; Finkral et al., 2012; Ottmar 2014). Charcoal has different decomposition properties than uncharred biomass, and therefore implications for carbon sequestration and future greenhouse gas releases to the atmosphere (DeLuca and Aplet, 2008). Terrestrial and atmospheric effects of pile burning, however, may depend on fuel and combustion characteristics (e.g., Johnson, 1984; Hardy, 1996).

Pile attributes (i.e., size, shape, age, species composition, packing ratio, bulk density) have been shown to have a significant effect on biomass and emissions estimates (Hardy, 1996; Wright et al., 2010), and are likely to affect combustion characteristics (i.e., intensity, duration, ratio of flaming to smoldering combustion, consumption quantity), carbon pools and fluxes (i.e., emissions quantities, charcoal formation), soil properties (i.e., organic matter content, pSOM quantities, nutrient availability, and hydrophobicity), and vegetation response (seed bank status; tree crown, bole, and root damage; revegetation rate; invasive species colonization). Pile attributes also change over time as gravity and snowpack compact collected fuel particles, as woody material cures, and as foliage dries and detaches from branch wood. Piled fuels may be left in the forest for a winter or even longer before disposal by burning. No research that we know of has systematically investigated the effects on fuels, combustion dynamics, soils, and vegetation of burning piled fuels of different ages under different environmental conditions.

With this in mind, we constructed and burned hand piles to examine how piles change with time and how those changes affect the duration and intensity of pile combustion, the amount of biomass consumed, and charcoal formation when burned in different seasons. Although pile construction methods and pile sizes vary, we chose to study hand piles of modest size (approximately 4 m^3) as these are typical for many "thin from below" fuel treatments employed in dry conifer forests in the western U.S. The primary objectives of the research were to determine: (1) how pile properties change with time, (2) how pile age and burn season affect combustion duration and intensity, (3) how pile age and burn season affect fuel consumption and charcoal formation, and (4) whether effects of pile age and burn season differ regionally. Providing forest managers and fire practitioners with detailed, quantitative information about hand-pile burning will inform management decisions about when to burn and how to minimize potential negative emissions, carbon, soil, and vegetation impacts.

2. Methods

2.1. Study areas

Two 2–3 ha sites, one each on the Santa Clara Pueblo in north-central New Mexico (hereafter New Mexico or NM) and the Naches Ranger District of the Okanogan-Wenatchee National Forest in central Washington (hereafter Washington or WA), were selected for study. Both sites were in dry conifer forests that had been recently thinned of small diameter (< 20 cm diameter at breast height [d.b.h.]) trees to reduce stand density. Thinning debris at both sites had been piled by hand; piles were approximately 2.5–3 m in diameter and 1.2–1.5 m tall. Piles at the New Mexico site were composed of < 7.6 cm diameter woody material only (branches and small tops), whereas the piles at the Washington site included tops, branch wood, and 1.5–2 m long pieces of bole wood up to approximately 20 cm in diameter.

The New Mexico site was located approximately 20 km west of Española in the Jemez Mountains (N 36°00′56.4″; W 106°16′59.9″). Piles were constructed on relatively flat ground at 2400 m elevation in a mature ponderosa pine (*Pinus ponderosa*) stand (mean d.b.h. = 29 cm) that was thinned in 2011 to a basal area of 19 m^2 ha^{-1}. Thinning debris was made available for firewood cutting prior to piling, effectively removing bole wood from the site. Remaining branches and tops were piled by hand to a density of 50 piles ha^{-1} (approximately 4% ground coverage). Total understory vegetation coverage was 21%, and was dominated by blue grama (*Bouteloua gracilis*), prairie Junegrass (*Koeleria macrantha*), and awnless brome (*Bromus inermis*). The site is characterized by a monsoonal climate regime with hot summers (mean summer maximum temperature of 27 °C) and cold winters (mean winter minimum temperature of –9 °C) that receives 56 cm of precipitation annually, with approximately half falling during the summer and early fall monsoon period (Prism Climate Group, 2016). Soils are well-drained Totavi gravelly loam (Natural Resources Conservation Service, 2015).

The Washington site was located above Rimrock Lake, approximately 50 km southeast of Mt. Rainier, in the eastern Cascade Range (N 46°39′27″; W 121°09′26.8″). Piles were constructed on gently sloping terrain (5–15% slope) on an easterly aspect at 1,130 m elevation in a mixed-conifer stand that was thinned in 2011 to a basal area of 10 m^2 ha^{-1}. The stand was comprised of a mixture of 15–20 cm d.b.h. ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), and grand fir (*Abies grandis*), with scattered, remnant, old-growth (70–125 cm d.b.h.) ponderosa pines and western larches. Thinning debris was piled by hand to a density of 90 piles ha^{-1} (approximately 7% ground coverage). Total understory vegetation coverage was 56%, and was 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 area is characterized by aspects of both continental and maritime climate regimes with warm, dry summers (mean summer maximum temperature of 23 °C; July-August precipitation of 3 cm) and cold, wet winters (mean winter minimum temperature of –5 °C; December-February precipitation of 43 cm); most precipitation falls as snow (Prism Climate Group, 2016). Soils are well-drained McDanielake ashy sandy loam (Natural Resources Conservation Service, 2015).

2.2. Study design

To test for potential differences in the effects of burning piles of different ages in different seasons (i.e., spring and fall burns) we employed a blocked (2 locations) factorial design (5 pile ages × 2 burning seasons) with replication (5 replicates per factor combination) for a total of 100 piles (Fig. 1). Immediately before the first fall and spring burning period we built 25 hand piles of equal size and approximately

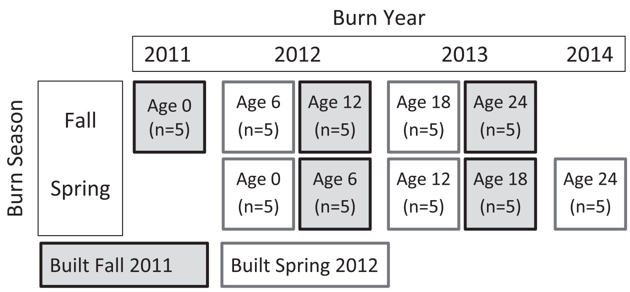

Fig. 1. Experimental design and treatment timeline. A total of 99 piles of five different ages (months) were burned under spring and fall burning conditions at the Santa Clara site in New Mexico (n = 50) and the Naches site in Washington (n = 49). One pile in Washington was inadvertently burned during unrelated management operations and excluded from the analysis.

equal weight at each location from among the already thinned and piled fuels present at each site. Five replicates from each build period were burned each season (spring and fall burns) at each location (New Mexico and Washington) for two years (pile ages of approximately 0, 6, 12, 18, and 24 months) following building to achieve a fully crossed, factorial experimental design. 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.

Piles were composed of coniferous thinning debris and sized to reflect typical hand piling in the western U.S. (i.e., half spheres or ellipsoids with a 1.2 m radius, 1.2 m tall). The material in each pile was weighed during the pile-building process with hanging scales. Material used for pile building was all ≤7.6 cm in diameter at the New Mexico site whereas, at the Washington site, piled material was separated into two size classes (≤7.6 cm and > 7.6 cm diameter) during pile building. Piles at the Washington site were constructed by alternating layers of ≤7.6-cm and > 7.6-cm diameter material and also included a layer of waxed, craft paper as a cover that was inserted under the top-most material on the pile to hold it in place. Piles are often covered with paper or polyethylene sheeting to keep the fuels dry, which allows for easier ignition under moist or wet weather conditions.

Pile weight measurements were corrected to a dry-weight basis by collecting representative moisture content subsamples for each pile. All moisture content subsamples were sealed in heavy-gauge, air-tight, plastic bags, weighed in the field with a precision balance within eight hours of collection, and returned to the laboratory for oven drying. Moisture content subsamples were oven-dried at 100 °C for at least 48 h and re-weighed to determine gravimetric moisture content, which was calculated as a fraction of net dry weight.

Piles were burned during the typical spring and fall burning windows at each location (Table 1). For logistical and safety reasons, piles were ignited one-at-a-time with a drip torch approximately every 15–20 min. The entirety of the ignition period typically extended over a 1.5–3 h window of time. Piles were allowed to burn unmanipulated until they self-extinguished (i.e., piles were not "chunked" – "chunking" is the act of moving unburned debris toward the center of an actively burning pile – a common practice in operational pile burning to maximize fuel consumption); only logs that rolled off of the pile and out of the actively burning area in Washington were moved back onto the main fire.

2.3. Data collection

Pile height was re-measured prior to burning to determine the degree to which each pile had compacted and changed volume since being built. Pile weight was adjusted to account for loss through decomposition between the date that piles were built and the date they were burned by applying site-specific negative exponential decay curves of the form $X/X_0 = e^{-kt}$, where X_0 is the starting dry weight, X is the weight at time t (in years), and k is the decay-rate constant (Olson 1965). Decay-rate constants for Washington ($k = 0.027\ yr^{-1}$) and New Mexico ($k = 0.064\ yr^{-1}$) were derived from repeated weighing of five undisturbed piles at each study site (Wright et al., 2017).

Starting bulk density (kg m^{-3}) was calculated by dividing pile dry weight by pile volume at the time of construction, and pre-burn bulk density was calculated by dividing pile dry weight adjusted for decomposition by pile volume adjusted for compaction at the time of burning.

Two to ten small (< 2.5 cm diameter branch wood and foliage) fuel moisture content samples were collected before ignition from the surface of neighboring piles that were not part of the experiment to assess fuel moisture conditions at the time of burning. In Washington, three large (> 7.6 cm diameter bole wood and bark) fuel moisture content samples were also collected. All material was sealed in heavy-gauge, air-tight, plastic bags, weighed in the field with a precision balance within eight hours of collection, oven-dried at 100 °C for a minimum of 48 h, and then re-weighed to determine gravimetric fuel moisture content (percent). Weather conditions (temperature, relative humidity, and wind speed) on each burn day (Table 1) were measured on-site (Washington) or nearby (New Mexico) with an automated, logging weather station.

The duration of flaming combustion (min) was timed for each pile. We also estimated flame height (m) every 1–3 min for the first 20 min 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.

Upon completion of all combustion, the original pile perimeter and two 0.60 m^2 wedge-shaped areas (Fig. 2) were delineated with aerosol paint. All residual organic material in these wedge-shaped areas was collected and returned to the laboratory for further processing. Ash on the soil surface was not collected, although we did attempt to collect all identifiable charcoal fragments, regardless of size. In the laboratory, charcoal fragments were separated from unburned and charred wood. The outer layer of charcoal was physically separated from charred wood using various scrapers and hand tools. All material was oven-dried at 100 °C for a minimum of 48 h and weighed on a precision balance. Fuel consumption (percent of pre-burn weight) was determined by subtracting the weight of residual material (i.e., the sum of wood and charcoal adjusted for sub-sampling fraction) from the pre-burn pile weight (i.e., the day-of-burn weight derived from applying the negative exponential decay-rate curves to the starting weight) and dividing by the pre-burn pile weight. The charcoal fraction (percent of pre-burn weight) was calculated as the weight of charcoal adjusted for sub-sampling fraction divided by the pre-burn pile weight.

2.4. Data analysis

We tested for differences in starting pile properties (i.e., pile weight and bulk density) between sites by using Welch's two sample t-tests (Zar, 1984), followed by 2-factor analysis of covariance (ANCOVA; Gotelli and Ellison, 2004) to evaluate how pile properties (i.e., pre-burn pile weight, bulk density, and height) may have been affected by pile age and site; burn season was not included in evaluations of pre-burn pile properties as we did not expect them to vary with burn season. Pile age was included as an interval variable in each model. Site was included as a categorical, fixed effect. Each response variable was examined separately. Where there was a significant site effect, we repeated the analysis for each of the sites separately with pile age as the single, main effect.

We used 3-factor ANCOVA (Gotelli and Ellison, 2004) to evaluate how pile age, burn season, and site affected the following response variables: peak flame height, flaming duration, fuel consumption, and charcoal fraction. Pile age was included as an interval variable, and burn season and site were categorical, fixed effects; each response

Table 1
Pile build and burn dates, pile ages at burning, day-of-burn weather, and day-of-burn fuel moisture conditions.

	Build Date (mm/dd)			Pile Age (months)		Day-of-burn Weather			Fuel Moisture (%)	
Burn Period	Fall (2011)	Spring (2012)	Burn Date (mm/dd)	Fall Build	Spring Build	Temp (°C)	RH (%)	Wind speed (km hr^{-1})	Small[a]	Large[b]
Santa Clara, New Mexico[c]										
Fall 2011	10/13	–	10/25	0.6	–	14	23	10.0	10.9	–
Spring 2012	10/13	04/09	04/10	6.0	0.2	15	25	10.5	11.5	–
Fall 2012	10/17	04/16	11/15	13.2	7.3	6	20	10.5	10.6	10.4
Spring 2013	10/20	04/16	03/12	17.0	11.1	8	31	8.0	17.4	–
Fall 2013	10/20	04/30	10/17	24.3	17.8	8	35	8.2	32.6	–
Spring 2014	–	04/16	02/06	–	21.8	−7	84	8.5	19.9	–
Naches, Washington[d]										
Fall 2011	08/23	–	10/18	1.9	–	12	48	1.4	31.0	70.0
Spring 2012	08/17	05/22	06/12	10.1	0.7	17	59	1.4	25.9	53.3
Fall 2012	08/25	05/24	10/31	14.5	5.3	9	100	0.0	57.5	39.0
Spring 2013	09/20	06/12	05/30	21.0	11.7	12	54	3.2	37.8	42.0
Fall 2013	08/24	06/13	10/29	26.6	16.8	5	54	0.0	36.2	31.3
Spring 2014	–	06/12	05/13	–	23.3	16	27	1.6	22.7	36.3

[a] Small fuel moisture samples consisted of foliage and branches < 2.5 cm in diameter collected from the exterior of adjacent piles.
[b] Large fuel moisture samples consisted of bole cross sections 2.5 cm thick and > 7.6 cm in diameter collected from the exterior of adjacent piles.
[c] Day-of-burn weather measurements are from the Tower New Mexico Remote Automated Weather Station 27 km south of, and approximately 400 m lower than the New Mexico study site.
[d] Day-of-burn weather measurements taken from onsite weather station (Spectrum Watchdog 2000).

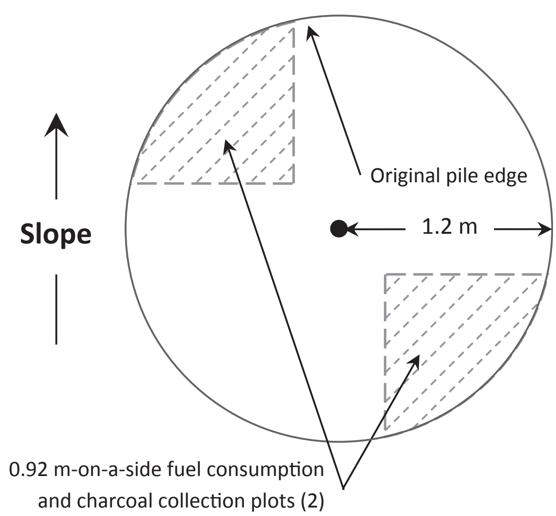

Fig. 2. Post-fire fuel consumption and charcoal sampling layout. All woody material and charcoal inside the wedge-shaped plot boundaries was collected for determining fuel consumption and charcoal production.

variable was examined separately. All 3-factor analyses were limited to two-way interactions (i.e., pile age × burn season, pile age × site, and burn season × site). Where there was a significant site effect for a response variable, we repeated the analysis for each of the sites separately, focusing on pile age and burn season as fixed, main effects.

By virtue of the experimental design (i.e., burning piles of two different ages on the same day for four of six burn days at each site), the fuel moisture variable was not fully crossed, preventing us from evaluating the effects of pile age. Small fuel moisture measurements were compared between sites for each season and between seasons for each site by using Welch's two sample *t*-test. Owing to the presence of large diameter fuels only at the Washington site, large fuel moisture measurements were only compared between seasons.

Some response variables were transformed to meet the assumptions of homogeneity of variance and normal distribution of residuals required of general linear models, such as ANCOVA. Bulk density, flaming duration, and charcoal fraction were natural log transformed, pre-burn pile weight was square root transformed, and fuel consumption was converted to a proportion and arcsine square root transformed.

We also examined potential relationships between measured pile properties (i.e., fuel moisture, degree of compaction as measured by change in pile height, and pre-burn fuel loading) and our fire behavior-(peak flame height, flaming duration) and fire effects-(fuel consumption, charcoal fraction) based response variables by using ordinary least squares linear regression (Neter et al., 1990). Regression analyses were conducted both for individual sites and for both sites pooled together in an attempt to expand the range of the independent variables of interest; reported regression slopes are for untransformed variables.

One pile in Washington was inadvertently burned during unrelated management operations and excluded from the analysis, leading to an unbalanced experimental design, which required that all multi-factor general linear models utilize a Type-II, partial sum-of-squares calculation methodology (Langsrud, 2003). Statistical significance for tests was evaluated at $\alpha = 0.05$. All statistical analyses were performed with R base package version 3.4.3 (R Development Core Team, 2017) and the 'car' package version 3.0-0 (Fox and Weisberg, 2011). Except when noted, results are reported as the mean ± one standard error.

3. Results

3.1. Effects of experimental factors: site, pile age, and burn season

3.1.1. Pile properties

Piles in New Mexico and Washington were composed of coniferous thinning material with different piece sizes. Although all piles in the study were built to the same dimensional specifications (i.e., height, diameter, shape), piles at the Washington site included pieces of large woody material > 7.6 cm in diameter that were missing from the New Mexico site, yielding piles with significantly different mean starting dry weight ($t_{65.1} = 26.1$, $P < 0.001$) and bulk density ($t_{58.5} = 25.3$, $P < 0.001$; Table 2). The mean starting dry weight and bulk density of the New Mexico piles were approximately one third those of the Washington piles.

Some of the physical characteristics of the piles changed with time. Measurements during the two and a half years of the experiment showed that the piles compacted as they aged (Fig. 3a). Piles became significantly shorter over time ($F_{1,95} = 61.34$, $P < 0.001$) irrespective of site ($F_{1,95} = 0.93$, $P = 0.34$) with pile-age-related reductions in height ranging from 14 to 35% in Washington and 15 to 36% in New Mexico depending on how much time had elapsed between pile building and burning; there was no pile age × site interaction for

Table 2
Starting and pre-burn pile characteristics for study sites in Washington and New Mexico. Fifty piles were constructed at both study sites.

	Washington		New Mexico	
	Mean ± SE	Range	Mean ± SE	Range
Starting characteristics				
Dry weight (kg)	209.0 ± 4.6	132.5–265.4	78.1 ± 1.9	47.4–112.7
Bulk density (kg m^{-3})	66.2 ± 1.7	41.0–91.3	21.6 ± 0.5	13.1–31.2
Height (m)	1.20 ± 0.00	1.10–1.20	1.20 ± 0.00	1.20
Pre-burn characteristics				
Dry weight (kg)	203.0 ± 4.7	124.7–255.4	73.5 ± 2.0	44.6–106.6
Bulk density (kg m^{-3})	89.9 ± 2.9	56.9–151.4	27.9 ± 0.9	16.3–43.6
Height (m)	0.87 ± 0.02	0.60–1.20	0.89 ± 0.02	0.57–1.20

change in pile height ($F_{1,95} = 0.21$, $P = 0.65$). Although significantly different between sites when built (Table 2) and in the pre-burn state ($F_{1,95} = 705.32$, $P < 0.001$), pile bulk density did not change significantly as piles aged ($F_{1,95} = 1.46$, $P = 0.23$) at either site (Fig. 3b), nor was there a significant pile age × site interaction ($F_{1,95} = 0.04$, $P = 0.85$). Because of the strong effect of site on bulk density, we examined the effect of pile age on bulk density separately for each site, but found no significant effect of pile age either in New Mexico ($F_{1,48} = 0.52$, $P = 0.48$) or Washington ($F_{1,47} = 1.00$, $P = 0.32$). As with bulk density, pile weight was significantly different between sites when the piles were built (Table 2) and in the pre-burn state ($F_{1,95} = 825.69$, $P < 0.001$), however, in contrast to bulk density, pile weight did decrease significantly as piles aged ($F_{1,95} = 9.83$, $P = 0.002$; Fig. 3c); the pile age × site interaction was not significant ($F_{1,95} = 0.19$, $P = 0.67$). Upon examination of the effect of pile age alone on pre-burn pile weight for each site, we found a significant effect in New Mexico ($F_{1,48} = 11.43$, $P = 0.001$), but not Washington ($F_{1,47} = 2.46$, $P = 0.12$).

3.1.2. Fuel moisture

The climate regimes in the two study sites differ, with both also experiencing distinct seasonal patterns of temperature and precipitation. The moisture content of small fuels, however, is largely a function of prevailing weather conditions (temperature, humidity, precipitation, and wind speed) at the time of sampling (Van Wagner 1979). In our study the effects of site and burn season on small fuel moisture were variable (Fig. 4). Mean small fuel moisture ranged from 23 to 58% in Washington and from 11 to 33% in New Mexico. Small fuels were significantly wetter in Washington for fall ($t_{12.5} = -2.90$, $P = 0.013$) and spring burns ($t_{7.9} = -2.66$, $P = 0.029$). Seasonal differences in small fuel moisture within sites were not significant for Washington ($t_{11.7} = 1.82$, $P = 0.095$) or New Mexico ($t_{26.8} = 1.32$, $P = 0.198$). Large fuel moisture is a function of the cumulative effect of antecedent weather from 10 s to 1000 s of hours prior to the moment of sampling, depending largely on particle size. Mean large fuel moisture ranged from 31 to 70% (Washington only) and did not differ significantly between spring and fall burns ($t_{14.8} = 0.37$, $P = 0.72$).

3.1.3. Fire behavior: peak flame height and flaming duration

The peak flame height in New Mexico (5.3 ± 0.6 m) was significantly higher than in Washington (3.7 ± 0.6 m; $F_{1,92} = 78.23$, $P < 0.001$). In Washington, peak flame height varied significantly by burn season ($F_{1,45} = 23.82$, $P < 0.001$), but was generally not affected by pile age ($F_{1,45} = 0.04$, $P = 0.83$), although this appeared to be dependent upon the burn season (significant pile age × burn season interaction; $F_{1,45} = 10.54$, $P = 0.002$; Fig. 5a). In New Mexico, peak flame height decreased consistently with increasing pile age ($F_{1,46} = 45.05$, $P < 0.001$; Fig. 5b), but burn season did not affect peak flame height ($F_{1,46} = 0.39$, $P = 0.53$), nor was there a significant interaction between burn season and pile age ($F_{1,46} = 2.79$, $P = 0.10$).

Piles burned during the flaming phase of combustion for between 15 and 91 min (46 ± 3 min) in New Mexico and between 22 and 221 min in Washington (95 ± 8 min). Among site, pile age, and burn season, only site was a significant factor affecting the duration of flaming combustion in the 3-factor ANCOVA ($F_{1,92} = 47.58$, $P < 0.001$). In Washington, flaming duration differed significantly for piles of different age ($F_{1,45} = 5.13$, $P = 0.03$) that were burned in different seasons ($F_{1,45} = 2.89$, $P = 0.10$), however the effect of pile age depended on the burn season (pile age × burn season interaction; $F_{1,45} = 18.48$, $P < 0.001$). When piles in Washington were burned in the spring flaming duration increased with increasing pile age, whereas this apparent relationship was reversed for piles burned in the fall (Fig. 5c). In New Mexico, flaming duration increased with increasing pile age ($F_{1,46} = 68.60$, $P < 0.001$), and was slightly longer in the fall ($F_{1,46} = 5.16$, $P = 0.03$); there was no significant interaction between pile age and burn season ($F_{1,46} = 1.64$, $P = 0.21$; Fig. 5d).

3.1.4. Fire effects: fuel consumption and charcoal formation

Fuel consumption ranged from 77 to 99% of pre-burn biomass on an individual pile basis, with means of 95.1 ± 0.4% and 89.9 ± 0.7% at the Washington and New Mexico sites, respectively. Fuel consumption was significantly higher at the Washington site than the New Mexico site ($F_{1,92} = 61.32$, $P < 0.001$). In Washington, pile age did not consistently affect fuel consumption ($F_{1,45} = 2.57$, $P = 0.12$), nor was there a consistent effect of burn season ($F_{1,45} = 0.13$, $P = 0.72$), however the pile age × burn season interaction was significant ($F_{1,45} = 4.91$, $P = 0.03$; Fig. 6a). In contrast, fuel consumption decreased with increasing pile age in New Mexico ($F_{1,46} = 16.58$, $P < 0.001$) and fuel consumption was significantly higher in the spring than in the fall ($F_{1,46} = 4.52$, $P = 0.04$); the pile age × burn season interaction was not significant ($F_{1,46} = 0.18$, $P = 0.67$; Fig. 6b).

The amount of charcoal present onsite following burning varied across a relatively narrow range, with 2.5 ± 0.1 kg $pile^{-1}$ and 1.9 ± 0.1 kg $pile^{-1}$ on average for burned piles at the sites in Washington and New Mexico, respectively. This represents

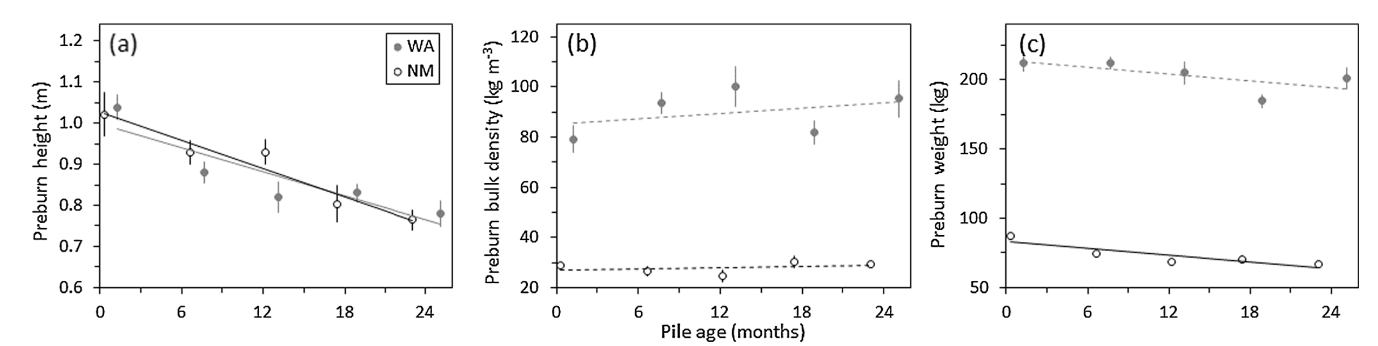

Fig. 3. Mean (a) change in pre-burn pile height, (b) pre-burn bulk density, and (c) pre-burn weight as a function of pile age for sites in New Mexico (NM) and Washington (WA). Solid lines indicate statistically significant differences in response variables. Error bars denote one standard error.

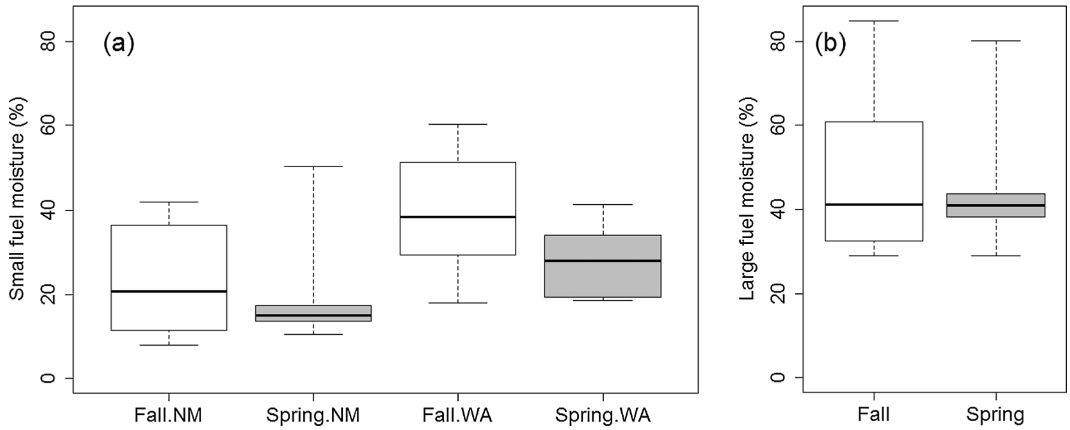

Fig. 4. Mean (a) small fuel moisture in Washington and New Mexico as a function of burn season for each site and (b) large fuel moisture as a function of burn season in Washington. Boxes represent the upper and lower quartiles with the median indicated by a horizontal line, whiskers represent the maximum and minimum values measured.

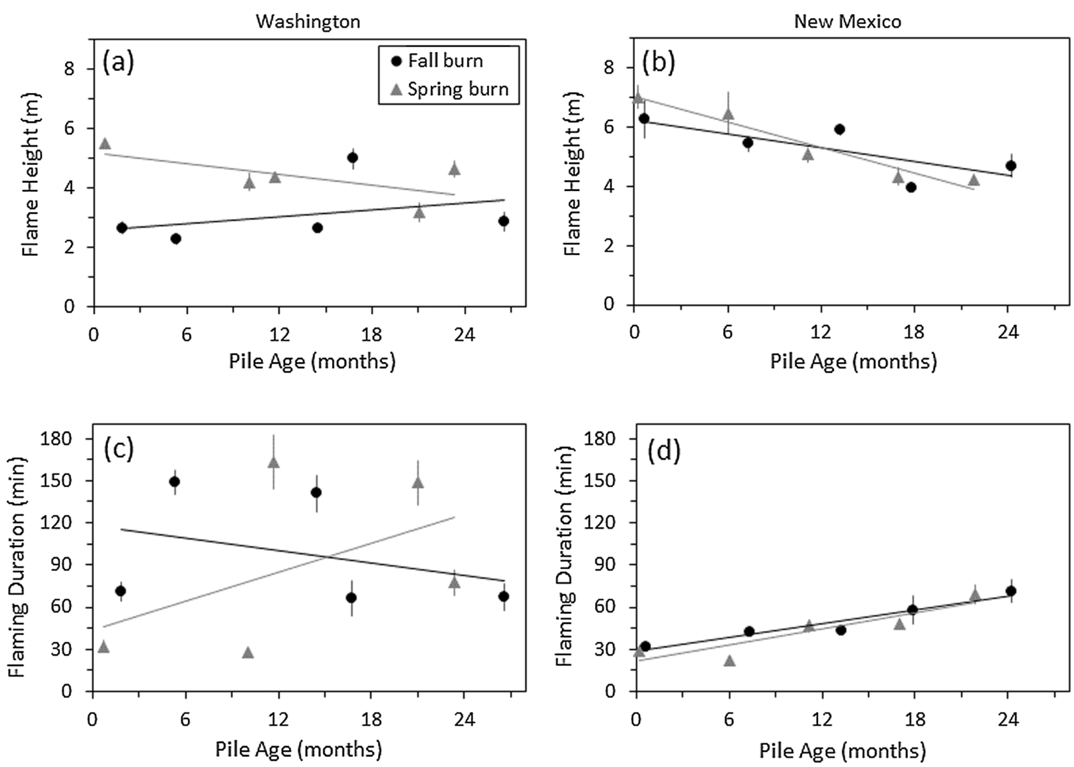

Fig. 5. Mean peak flame height in (a) Washington and (b) New Mexico as a function of pile age and burn season, and mean flaming duration in (c) Washington and (d) New Mexico as a function of pile age and burn season. Solid lines indicate statistically significant differences in response variables. Error bars denote one standard error.

approximately 30% of the residual post-burn biomass for both sites, or 0.3–2.1% of pre-burn biomass in Washington (1.2 ± 0.1) and 0.6–7.1% in New Mexico (2.8 ± 0.2). As with fuel consumption, the fraction of the pre-burn biomass that remains onsite as charcoal after the piles are burned was affected by the site factor ($F_{1,95} = 59.31$, $P < 0.001$). In Washington, pile age ($F_{1,45} = 0.16$, $P = 0.69$) and burn season ($F_{1,45} = 3.83$, $P = 0.06$) did not affect the fraction of the pre-burn biomass converted to charcoal; the pile age × burn season interaction was also not significant ($F_{1,45} = 0.81$, $P = 0.37$; Fig. 6c). As in Washington, the charcoal fraction in New Mexico was not affected by pile age ($F_{1,46} = 1.04$, $P = 0.31$) or burn season ($F_{1,46} = 2.09$, P = 0.16), and the pile age × burn season interaction was not significant ($F_{1,46} = 4.02$, $P = 0.051$; Fig. 6d).

3.2. Effects of measured variables: fuel moisture, compaction, and pre-burn weight

3.2.1. Fire behavior: peak flame height and flaming duration

We observed an inverse relationship between the length of time a pile burned and the intensity with which it burned. Flaming duration increased with decreasing peak flame height when considering piles from both sites together (slope = −17.9, $R^2 = 0.38$, $P < 0.001$) and for Washington (slope = −17.8, $R^2 = 0.22$, $P < 0.001$) and New Mexico (slope = −7.9, $R^2 = 0.29$, $P < 0.001$) when modeled separately (Fig. 7).

Small fuel moisture affected our fire behavior metrics, with wetter fuels tending to reduce intensity, but lengthen the amount of time piles burned. Peak flame height decreased with increasing small fuel

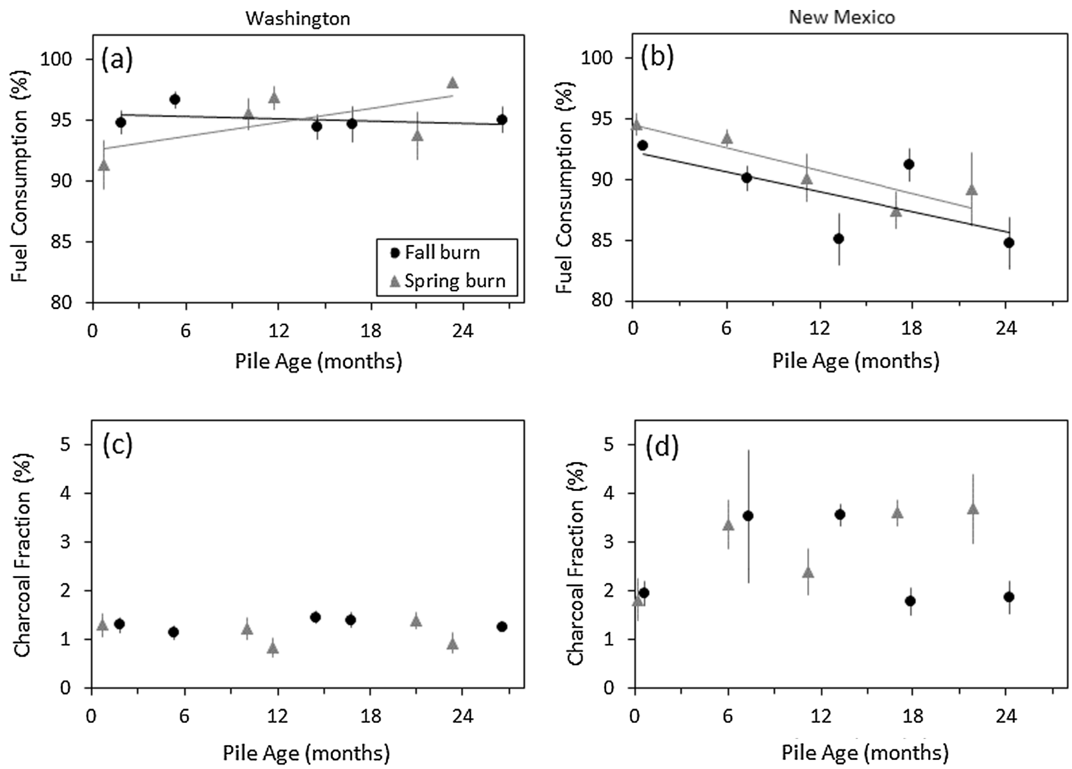

Fig. 6. Mean fuel consumption in (a) Washington and (b) New Mexico as a function of pile age and burn season, and mean charcoal fraction (percentage of pre-burn biomass converted to charcoal) in (c) Washington and (d) New Mexico as a function of pile age and burn season. Solid lines indicate statistically significant differences in response variables. Error bars denote one standard error.

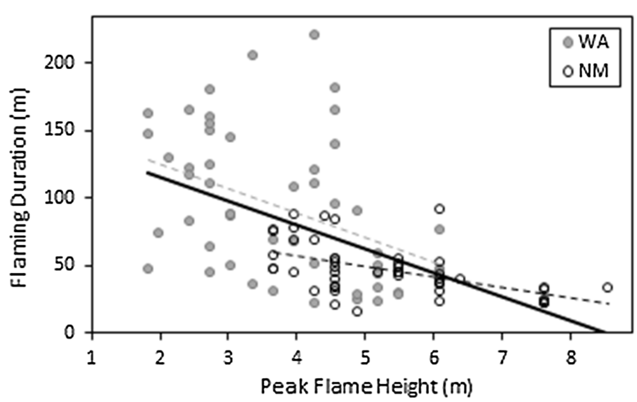

Fig. 7. Correlation between peak flame height and flaming duration. Lines indicate statistically significant linear regressions for data from both sites pooled together (solid black), from Washington only (dashed grey), and from New Mexico only (dashed black).

moisture when considering piles from both sites together (slope = −0.08, R^2 = 0.55, P < 0.001), and for piles in Washington (slope = −0.07, R^2 = 0.38, P < 0.001) and New Mexico (slope = −0.09, R^2 = 0.34, P < 0.001) when modeled separately (Fig. 8a). Conversely, flaming duration increased with increasing small fuel moisture when considering piles from both sites together (slope = 2.5, R^2 = 0.56, P < 0.001), and for piles in Washington (slope = 3.1, R^2 = 0.45, P < 0.001) and New Mexico (slope = 1.5, R^2 = 0.38, P < 0.001) when modeled separately (Fig. 8b). In Washington, large fuel moisture did not affect peak flame height (R^2 < 0.01, P = 0.78), but increasing large fuel moisture did tend to decrease flaming duration (slope = −1.4, R^2 = 0.11, P = 0.02, data not shown).

Piles compacted over time, which had a small, but significant effect on fire behavior. Peak flame height decreased as piles became more compact when considering piles from both sites together (slope = −0.04, R^2 = 0.12, P < 0.001), and for piles in Washington (slope = − = −0.04, R^2 = 0.14, P = 0.01) and New Mexico (slope = −0.04, R^2 = 0.14, P = 0.01) when modeled separately (Fig. 8c). Flaming duration increased as piles became more compact when considering piles from both sites together (slope = 0.78, R^2 = 0.06, P = 0.01), and for piles in New Mexico (slope = 0.69, R^2 = 0.15, P = 0.01), but not Washington (R^2 = 0.03, P = 0.25) when modeled separately (Fig. 8d).

In spite of our efforts to build piles of equal size and weight, we ended up with a range of pile weights both within and between the two sites. Peak flame height was lower for heavier piles when considering piles from both sites together (slope = −0.01, R^2 = 0.19, P < 0.001), but higher for heavier piles in New Mexico (slope = 0.03, R^2 = 0.14, P = 0.01), and Washington (R^2 = 0.07, P = 0.07) although not significantly so, when modeled separately (Fig. 8e). Flaming duration was longer for heavier piles when considering piles from both sites together (slope = 0.3, R^2 = 0.20, P < 0.001), but this apparent relationship was not significant for piles in Washington (R^2 < 0.01, P = 0.76), or piles in New Mexico (R^2 = 0.06, P = 0.08) when modeled separately (Fig. 8f).

3.2.2. Fire effects: fuel consumption and charcoal formation

Charcoal formation was correlated with fuel consumption. The fraction of the pre-burn weight converted to charcoal decreased with increasing levels of fuel consumption when considering piles from both sites together (slope = −0.15, R^2 = 0.42, P < 0.001) and for Washington (slope = −0.09, R^2 = 0.51, P < 0.001) and New Mexico (slope = −0.10, R^2 = 0.09, P = 0.03) when modeled separately (Fig. 9).

Fuel consumption increased with increasing small fuel moisture when considering piles from both sites together (slope = 0.11, R^2 = 0.13, P < 0.001), but not when modeling data for piles in

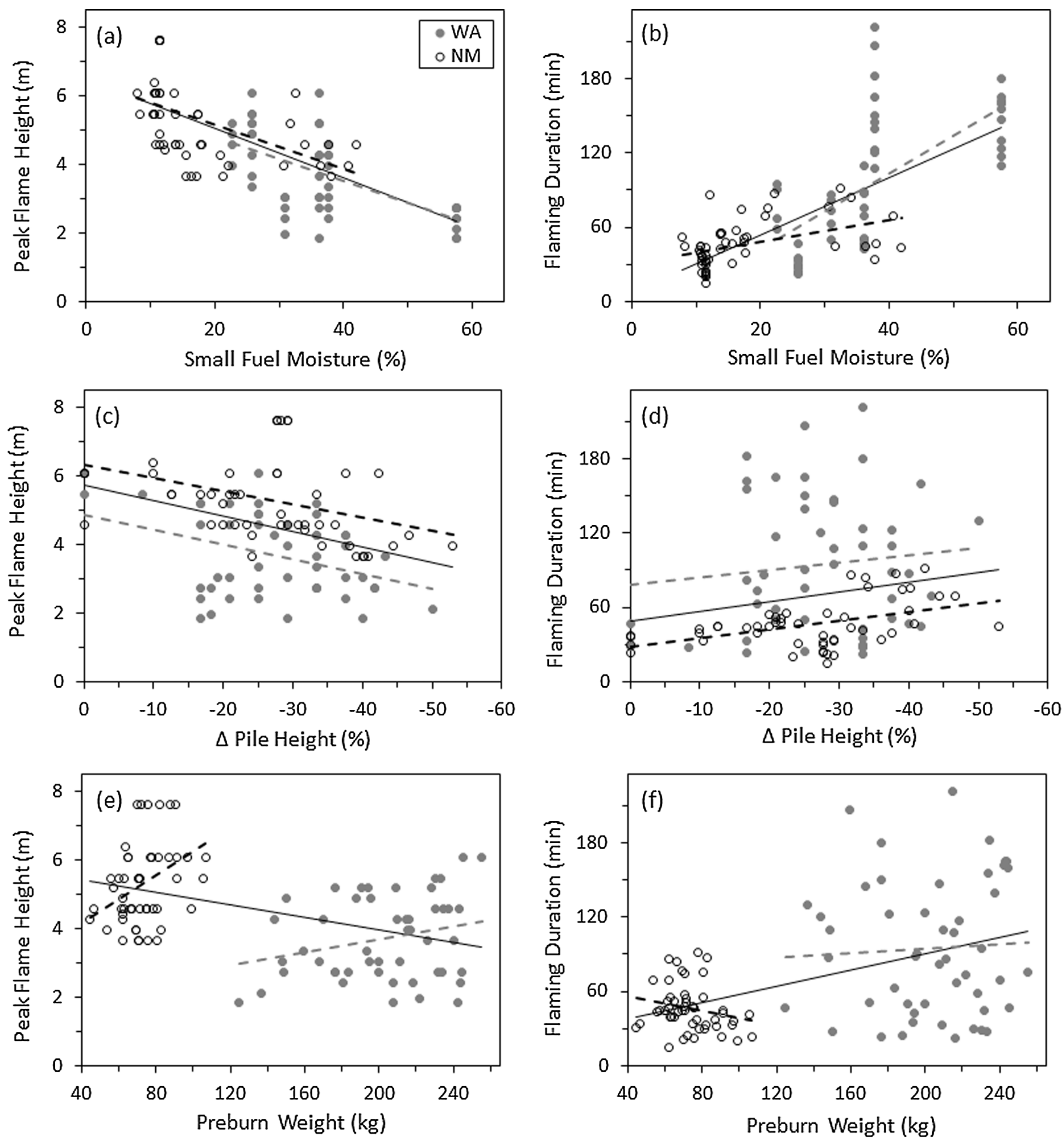

Fig. 8. Correlation between small fuel moisture and (a) peak flame height and (b) flaming duration, correlation between reduction in pile height (i.e., compaction) and (c) peak flame height, and (d) flaming duration, and correlation between pre-burn weight and (e) peak flame height, and (f) flaming duration for hand piles burned in Washington and New Mexico. Lines indicate linear regressions for data from both sites pooled together (solid black), from Washington only (dashed grey), and from New Mexico only (dashed black).

Washington ($R^2 < 0.01$, $P = 0.84$) or New Mexico ($R^2 = 0.07$, $P = 0.07$) separately (Fig. 10a). The fraction of the pre-burn weight converted to charcoal decreased with increasing small fuel moisture when considering piles from both sites together (slope $= -0.04$, $R^2 = 0.21$, $P < 0.001$), but not when modeling data for piles in Washington ($R^2 = 0.02$, $P = 0.34$) or New Mexico ($R^2 = 0.05$, $P = 0.12$) separately (Fig. 10b). In Washington, large fuel moisture did not affect fuel consumption ($R^2 = 0.03$, $P = 0.26$) or the charcoal fraction ($R^2 < 0.01$, $P = 0.85$).

Whereas pile compaction had a small effect on fire behavior metrics, we observed no relationship between compaction and fuel consumption or charcoal formation. Fuel consumption was unaffected as piles became more compact when considering piles from both sites together ($R^2 < 0.01$, $P < 0.94$), or piles in Washington ($R^2 = 0.05$, $P = 0.11$) or New Mexico ($R^2 = 0.06$, $P = 0.09$) when modeled separately (Fig. 10c). The fraction of pre-burn weight converted to charcoal was also unaffected as piles became more compact when considering piles from both sites together ($R^2 < 0.01$, $P = 0.64$), or piles in Washington ($R^2 < 0.01$, $P = 0.86$), or New Mexico ($R^2 < 0.01$, $P = 0.82$) when modeled separately (Fig. 10d).

The effect of pre-burn weight on fuel consumption and charcoal formation appeared to differ between the two study sites. Fuel consumption was higher for heavier piles when considering piles from both sites together (slope $= 0.04$, $R^2 = 0.37$, $P < 0.001$), and for piles in New Mexico (slope $= 0.15$, $R^2 = 0.21$, $P < 0.001$), but not Washington ($R^2 = 0.02$, $P = 0.33$) when modeled separately (Fig. 10e). Charcoal fraction was lower for heavier piles when considering piles from both sites together (slope $= -0.01$, $R^2 = 0.41$, $P < 0.001$), and for piles in New Mexico (slope $= -0.05$, $R^2 = 0.15$, $P = 0.01$), but this apparent relationship was not significant for piles in Washington ($R^2 = 0.04$, $P = 0.16$) when modeled separately (Fig. 10f).

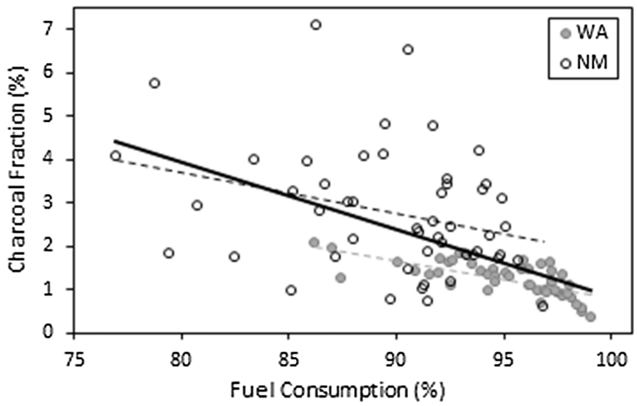

Fig. 9. Correlation between fuel consumption and charcoal fraction. Lines indicate statistically significant linear regressions for data from both sites pooled together (solid black), from Washington only (dashed grey), and from New Mexico only (dashed black).

4. Discussion

4.1. Pile properties

This study explicitly examined the effects of age and season-of-burn on the physical properties (size, weight, bulk density, moisture content), fire behavior (peak flame height, flaming duration), and fire effects (fuel consumption, charcoal production) for hand-constructed piles in Washington and New Mexico. Some properties of hand-piled slash changed with the passage of time. These changes have implications for combustion processes and fire behavior, which could potentially influence the resulting fire effects. Piles compact and lose biomass over time as indicated by the reduction in height and weight for piles of increasing age. The amount of compaction and biomass loss was similar for the two sites when viewed over the full term of the study. Based on our results it appears that biomass loss and compaction are not strongly affected by either pile composition (i.e., presence or absence of larger diameter woody material) or site factors, such as climate regime. Though the piles in our study compacted and became lighter, their bulk density (i.e., weight of fuel per unit of pile volume) did not change over time, suggesting that, at least for the first few years after construction, biomass loss due to decomposition occurs at the same rate as compaction (Wright et al., 2017). It is important to understand how pile properties vary over time, as phenomena like compaction influence availability of oxygen for combustion within the pile and also the balance of heat transfer processes (conduction, convection, and radiation) during burning, both of which influence the intensity and rate of burning (Byram, 1959).

Small fuels in Washington were typically wetter than small fuels in New Mexico for both spring and fall burns, although expected differences between seasons did not materialize for either site. Likewise, expected differences between seasons for large fuels, present only in piles at the Washington site, were not evident in our data set. Although mean fuel moisture did not differ between seasons, we did observe variation over a narrower range in the spring from year to year for both sites. Given the strong correlation between weather conditions and fuel moisture content (Van Wagner, 1979), and the relatively small number of burns in each season at each site, however, it is difficult to draw definitive conclusions about whether or how either site or season-of-burn affected piled fuel moisture. Nelson and Hiers (2008) found that both the amount and the orientation of fuel particles affected moisture dynamics for pine needle fuelbeds, therefore changes to the physical properties of piled fuels, such as occur when piles compact over time, will also likely affect how piled fuels dry as they age. Piles represent a different configuration of fuel particles than is found in naturally occurring forests or in broadcast slash in managed stands. Further study is necessary to understand how the moisture content of piled fuels fluctuates and whether piled fuel moisture is adequately represented by relationships derived from unpiled material.

4.2. Fire behavior

Changes in fuel properties associated with pile aging, principally the development of a more compacted fuelbed; differences in fuel properties attributable to site, including day-of-burn weather, fuel moisture, and pre-burn weight and composition (i.e., inclusion of larger diameter woody material in Washington but not New Mexico); and differences between burn seasons, at least in Washington, all affected how piles burned. Burns in New Mexico tended to be conducted under drier, windier conditions than in Washington. In addition, day-of-burn weather and fuel moisture was more consistent from burn-to-burn in New Mexico than in Washington. Whether observed differences in fire behavior metrics (peak flame height and flaming duration) are a function of our experimental factors (pile age, burn season, and site or pile composition), year-to-year variability in weather and fuel moisture, or likely both to some degree, is difficult to know definitively given the limits of our study design.

Acknowledging these complicating factors, we did find that peak flame height was negatively correlated with flaming duration, although this explained only a modest amount of the variance in the relationship between these variables ($R^2 = 0.22$ for Washington and $R^2 = 0.29$ for New Mexico). Fires that achieved higher peak flame heights, which were assumed to burn with greater combustion rates, burned fuels more quickly and therefore experienced shorter periods of flaming combustion. Although not surprising, this finding could be useful for deciding how to balance management objectives to minimize smoke emissions, as well as heat impacts on above- (e.g., tree crowns) and belowground (e.g., soils, seed banks, and rootstocks) resources. Burning piles before they become overly compacted and when they are relatively dry could minimize smoke emissions as the higher combustion rate and efficiency associated with those conditions will cause more of the fuel present to burn during the flaming phase of combustion, which releases the fewest emissions per unit of fuel consumed (Johansen, 1981; Ottmar et al., 2001). Conversely, if the risk is acceptable, waiting to burn piles, and burning when small fuels are wetter could mediate flame height thereby reducing potential crown scorch and torching in thinned stands, as we found that peak flame height tended to decrease with increasing small fuel moisture and increasing fuel compaction. This is consistent with our results that showed peak flame height decreased with increasing pile age for both burn seasons in New Mexico and for spring burns in Washington. Whether total fuel loading or presence of large woody material affected flame height was equivocal, as we noted a relatively modest ($R^2 = 0.19$) negative relationship between pre-burn pile weight and peak flame height when data from both sites were pooled, but weakly positive within-site relationships between weight and flame height ($R^2 = 0.07$ for Washington and $R^2 = 0.14$ for New Mexico).

Flaming duration increased with age for both burn seasons in New Mexico, with fall burns experiencing slightly longer flaming combustion than spring burns. The effects of pile age on flaming duration in Washington differed depending on burn season, with flaming duration generally increasing with age for spring burns and decreasing with age for fall burns. In general piles with wetter, more compacted fuels burned longer, but at a lower intensity as indicated by the lower peak flame heights. We also found, as have others (Johansen, 1981, 1984; Busse et al., 2013), that the amount of time a pile takes to burn is related to the amount of biomass in the pile, with inclusion of large woody material potentially increasing both the flaming duration and the overall (flaming + smoldering) combustion period. A lack of significance of the slopes for within-site regressions of flaming duration as a function of preburn pile weight does, however, warrant further testing to verify this apparent relationship. Whereas opting to burn when pile

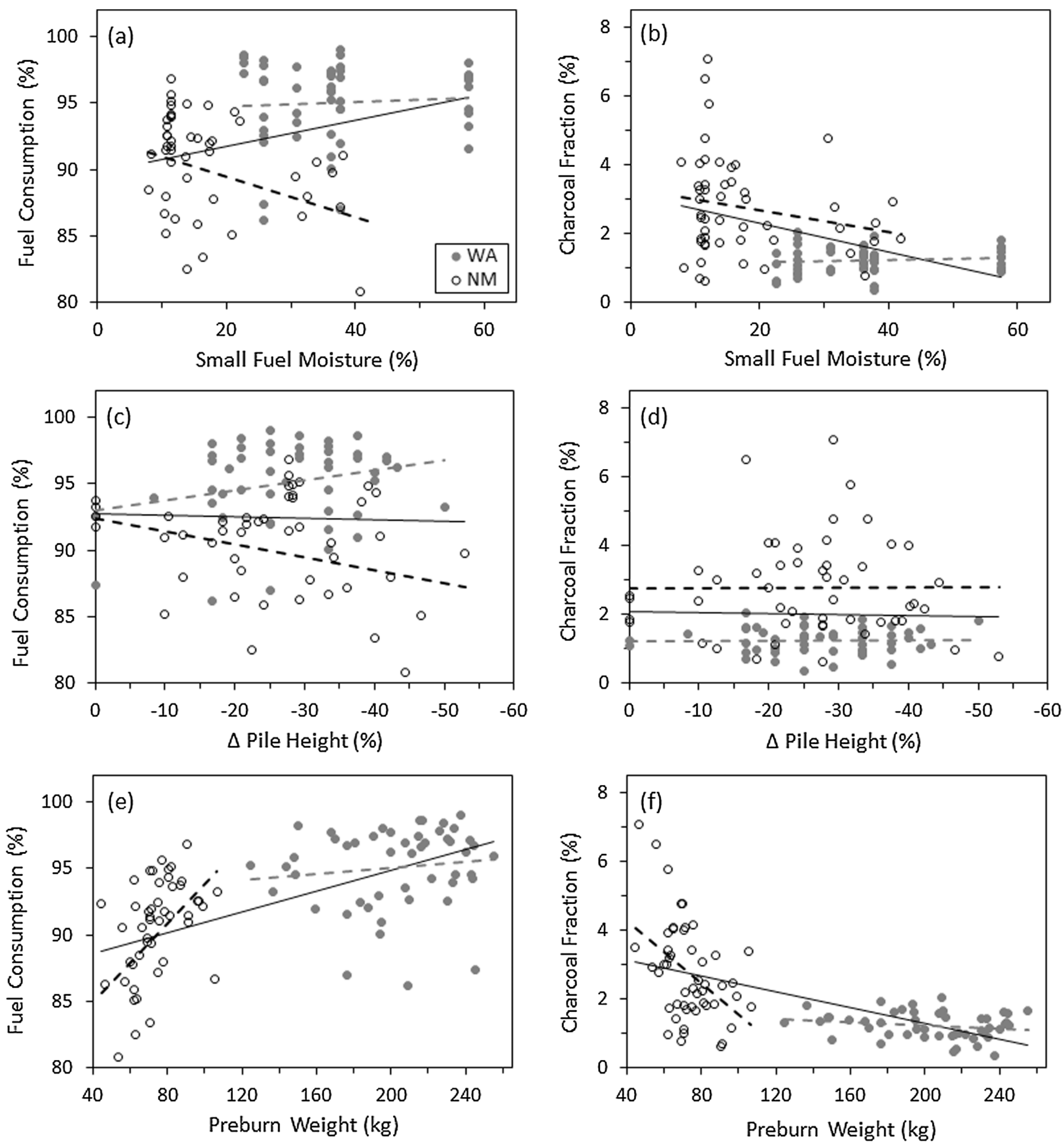

Fig. 10. Correlation between small fuel moisture and (a) fuel consumption and (b) fraction of pre-burn biomass converted to charcoal, between change in pile height and (c) fuel consumption and (d) fraction of pre-burn biomass converted to charcoal, and between pre-burn pile weight and (e) fuel consumption and (f) fraction of pre-burn biomass converted to charcoal for hand piles burned in Washington and New Mexico. Lines indicate linear regressions for data from both sites pooled together (solid black) and from Washington only (dashed grey) and from New Mexico only (dashed black).

properties could minimize flame height (i.e., wetter and more compacted) may reduce potential damage to aboveground resources such as the forest canopy, burning under such conditions tends to extend periods of flaming combustion and sustained heating of the soil surface and potentially deeper soil layers, which may have a negative effect on post-burn soil properties, mycorrhizal communities, and understory vegetation recovery (Busse et al., 2013).

Large fuel moisture did not appear to affect peak flame height, however, increasing large fuel moisture was significantly correlated with decreasing flaming duration, although this relationship only explained a small portion of the variability in the data ($R^2 = 0.11$).

Day-of-burn weather was quite variable both between seasons at a site and also within seasons, perhaps obscuring a seasonal signal in our data. Precipitation, temperature, wind speed, and relative humidity all likely had at least some effect on the intensity and rate with which our piles burned, although assigning or apportioning the effects of any weather variable to our fire behavior results is beyond the scope or capacity of our study design given the lack of control over weather conditions and the relatively small number of burn days. Accordingly, we will limit ourselves to a few anecdotal observations and only speculate about some of the more curious patterns in our data. First, it should be noted that burns in New Mexico occurred under substantially windier conditions than burns in Washington, perhaps partially accounting for the consistently higher peak flame heights in New Mexico. Given the difference in pile composition (i.e., lack of large woody material) in New Mexico, however, it is difficult to know the degree to which wind speed and fuel composition are driving fire intensity. Add in differences in fuel moisture between the sites and it becomes clear that the lack of within-site replication (i.e., multiple burn days for piles with and without large fuels at both sites) precludes us from meaningfully addressing this question. Second, although the range of wind speeds in Washington (0–3.2 km h^{-1}) was much lower than in New

Mexico (8.0–10.5 km h^{-1}), based on our observations in the spring of 2013 in Washington (see the spring burn symbols for piles that were approximately 12 and 18 months old in Fig. 5c) and in comparison to the other burn days, windier conditions may have effectively fanned the flames and delayed the onset of smoldering combustion. Third, light precipitation and high small fuel moistures on the day-of-burning in the fall of 2012 in Washington suppressed the vigor of burning, producing the lowest peak flame heights, and relatively high flaming duration (see the fall burn symbols for approximately 6 and 12 months old piles in Fig. 5a and c). We speculate that the lower combustion intensity associated with higher fuel moisture, lack of wind, and high humidity may have retarded the rate at which the small fuels in pile burned to completion, thereby lengthening the period of flaming duration.

4.3. Fire effects

In addition to attempting to determine whether pile age, burn season, and site or pile composition affected fire behavior, we also sought to understand how fire effects metrics were influenced by our experimental factors and other measured variables. Consumption of piled fuels was high, averaging 95% in Washington and 90% in New Mexico; measurements that agree well with the 90% estimated for hand piles by Finkral et al. (2012) for ponderosa pine piles in northern Arizona. Fuel consumption did vary with burn season and pile age in New Mexico; consumption was slightly higher for spring burns and decreased approximately 3.5% yr^{-1} for the two years of the study for both burn seasons. This is in contrast to piles in Washington where there was no difference between burn seasons, and for which the amount of consumption increased approximately 2.5% yr^{-1} for spring burns, but showed essentially no change with time for fall burns. Additional research is necessary to confirm apparent differences in fuel consumption with respect to burn season and pile composition (i.e., piles with (Washington) and without (New Mexico) larger material).

Though our analysis regressing small fuel moisture and fuel consumption appears to show consumption increasing with increasing small fuel moisture levels when data from Washington and New Mexico were pooled together, small fuel moisture did not have a measurable effect on fuel consumption at either study site when considered individually. The apparent pattern of increasing fuel consumption for wetter piles is likely confounded by the differences in pile composition and weight. Not unlike this study, Brown et al. (1991) found that fuel moisture alone was a poor predictor of fuel consumption for logging slash. Further measurement is necessary to elucidate the nature of the relationship between fuel moisture and fuel consumption for piled fuels.

The small difference in the overall amount and temporal pattern of percentage consumed between the two sites, and the weak ($R^2 = 0.02$ for Washington) to modest ($R^2 = 0.21$ for New Mexico) correlation between preburn weight and percentage consumption suggests that the composition of piles (i.e., the inclusion of large diameter pieces in Washington) may have a small effect on fuel consumption levels. Heavier, 3.5 m^3 hand piles in Washington had greater consumption than like-sized, but lighter hand piles in New Mexico. This pattern may extend to even larger and heavier piles, as Finkral et al. (2012) noted that fuel consumption for much larger machine-constructed piles averaged 99%.

Fuel consumption was negatively correlated with charcoal formation; charcoal fraction decreased significantly with increasing levels of consumption. The fraction of the preburn biomass that was converted to charcoal ranged from 0.3 to 2.1 (mean = 1.2) percent for piles at our study site in Washington, which is comparable to the 1.20 ± 1.18% (mean ± standard deviation) measured by Finkral et al. (2012). Charcoal fraction ranged from 0.6 to 7.1 (mean = 2.8) percent for piles at our study site in New Mexico, which is slightly higher on average than Finkral et al. (2012) noted, but comparable to the range of 1 to 8% of fuel consumed found by Pingree et al. (2012) during the Biscuit Fire in central Oregon, who, like us, found a negative correlation between fuel consumption and charcoal formation.

Unlike fuel consumption, charcoal fraction was not affected by pile age at either site; however, it was significantly higher for the piles in New Mexico, which also showed greater within-burn-day (i.e., larger error bars in Fig. 6d than c) and burn-to-burn variability (i.e., wider distribution of data points in Fig. 6d than c). Greater variability in New Mexico is surprising given the narrower range of preburn weight, day-of-burn weather, and fuel moisture conditions, suggesting that the processes dictating charcoal formation may differ for piles with and without large woody material – a principal difference between the study sites. Differences in within-site variability coupled with the significant, albeit weak, trend of decreasing charcoal formation with increasing pile weight overall and in New Mexico individually reinforces the speculation that the difference in pile composition between New Mexico and Washington may have contributed to the differences we measured in charcoal fraction. Whereas changes in pile compaction affected fire behavior, as with fuel consumption, it did not affect charcoal formation.

As with fuel consumption, the effects of small fuel moisture on charcoal fraction were equivocal. When pooling data from both sites, a significant regression suggests that charcoal fraction decreases with increasing small fuel moisture, however, site-specific regressions are not significant. Large fuel moisture levels had no effect on charcoal fraction in Washington. Additional research is necessary to determine whether or to what extent fuel moisture affects charcoal formation when burning piled fuels.

4.4. Management implications

Pile burning is a contributor to greenhouse gas emissions (Ter-Mikaelian et al., 2016), however, as we have noted, charcoal, a recalcitrant form of carbon, is also produced and stored on-site as a byproduct of pile burning. Based on measurements obtained during our study, pile burning is projected to sequester approximately 0.08 and 0.17 Mg C ha^{-1} in a recalcitrant form in the soil carbon pool at the New Mexico and Washington sites respectively, based on the ratio of carbon (C) to charcoal of 0.78 in burned, piled forest residues (Finkral et al., 2012). In comparison, broadcast prescribed burns with varying amounts and types of forest residues in a Sierra mixed conifer forest generated between 0.31 and 0.42 Mg C ha^{-1} in the organic horizon (Wiechmann et al., 2015), thinning treatments followed by prescribed burning in mixed ponderosa pine and Douglas-fir forests in western Montana were estimated to have yielded between 0.17 and 1.7 Mg C ha^{-1} (DeLuca and Aplet, 2008), and burning of larger slash piles in northern Arizona resulted in charcoal additions of between 0.05 and 0.34 Mg C ha^{-1} (Finkral et al., 2012). Fires do not always result in additions of charcoal, as Buma et al. (2014) found a decrease in charcoal for subalpine forests in the southern Rocky Mountains following high intensity wildfire. Even though charcoal can be lost from a site through erosion and combustion in future fires, repeated episodes of thinning and hand pile burning in managed, ponderosa pine-dominated forests, such as those typical of our study sites, are expected to result in small net additions of carbon that is highly decay resistant (DeLuca and Aplet, 2008).

Making the simplistic assumption that our study sites are representative of the annual acreage of piled fuels with respect to pile size, weight, and quantity, this suggests that between 2540 and 5830 Mg C could be added to the national soil carbon pool on an annual basis if the U.S. Forest Service alone were to continue burning piled fuels at the rate of 33,600 ha of piled fuels yr^{-1} achieved during the decade spanning 2005 to 2014. Such an addition is the equivalent of offsetting up to roughly 2.1 million gallons of diesel fuel combustion (EPA, 2018), thereby mitigating some of the greenhouse gas emissions impacts of mechanized forest management operations.

Managers are often constrained in their ability to conduct pile burns by weather, staffing or equipment availability, proximity to populated areas, air quality impacts, and other factors. This can result in piles aging and accumulating in the woods. Older piles (and piles burned when fuel moistures are higher) have shorter flame heights. Managers concerned about crown scorch may be able to use this effect of pile age to their advantage. If seeking greater fuel consumption, managers should aim for heavier piles. Conversely, managers seeking to minimize smoke emissions would do well to pursue strategies that minimize fuel consumption such as reducing pile weight and the quantity of large fuels incorporated into piles by maximizing utilization or permitting firewood cutting to reduce the amount of fuel that requires disposal by burning. Similarly, if charcoal production is desired to increase carbon sequestration or to improve soil properties, burning lighter piles could help achieve this objective.

Our experiment was designed to test the impacts of age and burn season on fire behavior during, and fire effects following pile burning, however it addressed only a relatively narrow range of the fuel characteristics and environmental conditions under which pile burning occurs in the United States. The large number of piles built and burned every year and the reliance on pile burning by fuel managers to dispose of hazardous fuels in stands with valuable standing timber and adjacent to populated areas justifies additional research on pile burning. Detailed research on moisture dynamics of piled fuels and the effect of fuel moisture on fire behavior, fuel consumption, and charcoal formation would greatly expand our understanding of how piles burn and how that affects carbon pools after burning. Previous studies have shown significant differences between spring and fall burns where fuel moisture was closely tied with season of burn (Kauffman and Martin, 1989). The fact that our study, in general, did not find a significant burn season effect may be due to a range of factors or a combination of them. Because we could not control for environmental conditions, moisture patterns did not necessarily match typical seasonal conditions for fuel moisture or weather. Different experimental designs focused on more closely controlling fuel moisture and weather variables are necessary to more clearly understand the effects of environmental conditions and burn season when burning piles. Our experiment focused on moderately sized (approximately 3.5 m^3), hand-built piles. Additional research is needed on a wider variety of hand-built piles (i.e., piles with a broader range of sizes and piece size distributions) and various types of machine-constructed piles before we can extend our inferences to larger piles.

Declaration of interests

The authors declared that there is no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2019.02.005.

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