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Comparison of Heat Transfer and Soil Impacts of Air Curtain Burner Burning and Slash Pile Burning

Woongsoon Jang [1,*], Deborah S. Page-Dumroese [2] and Han-Sup Han [3]

[1] Department of Forestry and Wildland Resources, Humboldt State University, Arcata, CA 95521, USA
[2] USDA Forest Service, Rocky Mountain Research Station, 1221 South Main, Moscow, ID 83843, USA; ddumroese@fs.fed.us
[3] Department of Forestry and Wildland Resources, Humboldt State University, Arcata, CA 95521, USA; hh30@humboldt.edu
* Correspondence: woongsoon.jang@gmail.com; Tel.: +1-707-826-3725

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Abstract: We measured soil heating and subsequent changes in soil properties between two forest residue disposal methods: slash pile burning (SPB) and air curtain burner (ACB). The ACB consumes fuels more efficiently and safely via blowing air into a burning container. Five burning trials with different fuel sizes were implemented in northern California, USA. Soil temperature was measured at 1, 2, 3, 4, 6, and 8 cm depth. Immediately after burning, soil samples from two depths (0–10 and 10–20 cm) and ash samples were collected for analyzing organic matter; carbon and nitrogen content; and calcium, magnesium, and potassium concentrations. The highest temperature observed was 389 °C at 1 cm depth under the SPB. Mean peak temperatures were 133.2 °C and 162.2 °C for ACB and SPB, respectively. However, there were no significant differences in peak temperatures and duration of lethal soil temperatures (total minutes over 60 °C) between ACB and SPB. Heat transfer decreased rapidly as the soil depth increased. There is little evidence that any subsequent changes in soil chemical properties occurred, concluding that these small-scale burns had few negative impacts at our study site. Therefore, given the lack of extreme soil heating and more efficient and safer woody residue reduction, the ACB may be more effective than open SPB, especially where fire escape or long-term fire damage to soils are of concern.

Keywords: forest residue management; woody biomass utilization; soil temperature profile; soil productivity; thermocouple

1. Introduction

Fire suppression and drought have led to a significant amount of land that must be treated to reduce wildfire risk [1], particularly in California, USA. There are many ecological benefits of forest residue disposal through burning [2,3], but selecting the most appropriate method is important for sustainable forest management [4]. Currently, piling residues is the preferred method for disposal of woody residues among land managers. As an effective fuel reduction tool, slash pile burning (SPB) has been widely used in western USA forests as one method to reduce fire risk and extreme fire behavior [3,5]. Large amounts of woody residues can be generated by thinning or removing dead trees and residue disposal can be a nuisance for land managers [6]. Pile burning has been preferred since it is relatively inexpensive and can usually be conducted in a controlled manner [7]. It also allows land managers to burn fuels safely under various weather conditions if correctly implemented [8]. Thus, SPB has often been selected as the most economically feasible option for disposing forest residues, especially at the wildland—urban interface or areas without local bioenergy facilities [3].

However, SPB also has limitations and challenges: piling and burning has been shown to alter soil chemical and physical properties such as clay mineralogy [9], loss of organic matter [10], and changes in base cation concentration [9,11]. In addition, building piles can cause considerable soil disturbances such as compaction, displacement, or rutting depending on the time of year when piles are created [12,13]. Unburned piles can be an ideal breeding area for pine engraver (*Ips pini*), thereby potentially increasing insect attack of surrounding live trees [4,14]. Although pile burning can be conducted under a wide range of weather conditions, low-fire risk days (e.g., days with low wind speed, cool temperature, and high humidity) are commonly recommended [7]. One of the most significant drawbacks of SPB is that it emits considerable smoke containing various air pollutants such as particular matter, CO, NOx, and volatile organic compounds [5]. As a result, burning could be restricted in areas near the public where emissions could negatively impact air quality [15].

An alternative method to dispose forest residues after harvesting is the air curtain burner (ACB), also known as air curtain destructor/incinerator (Figure 1a). ACBs are metal boxes (size: 5–53 m^3) with a high velocity air curtain blown across the top of the residue (see [16] for a description of the ACB). It minimizes many of the limitations of SPB. For example, it has higher combustion efficiency, thereby burning residues faster (Table 1). Compared to pile burning, it produces fewer air emissions [17]. Moreover, it can reduce the risk of spreading fire, insect breeding in unburned piles, and burning can occur under a wider range of weather condition [16]. Thus, the ACB could provide an environmentally acceptable or technically feasible (i.e., safe) method of woody residue management, but the impacts on soil chemical properties under it are largely unknown.

Figure 1. (**a**) Air curtain burner with ember case; and (**b**) slash pile burning (Photo credit: H.-S. Han).

Table 1. Description of climatic and fuel conditions for slash pile burning (SPB) and air curtain burner (ACB).

	Groveland Site						Volcano Site			
	Small [1]/Fresh		Mixed [2]/Fresh		Mixed/Cured		Small/Fresh		Mixed/Fresh	
	ACB	SPB	ACB	SPB	ACB	SPB	ACB	SPB	ACB	SPB
Air temperature (°C)	23.8		20.1		30.2		24.4		19.4	
Relative Humidity (%)	38.1		59.2		35.8		28.7		37.8	
Wind speed (km/h)	1.8		1.5		0.3		0.8		0.5	
Soil moisture (%)	13.7	18.1	17.0	16.2	9.6	8.7	6.7	7.4	9.2	9.5
Avg. Fuel size (diameter; cm)	5.1	4.9	18.9	17.2	15.7	14.2	6.0	6.1	15.8	17.0
Fuel moisture contents (%)	26.0	32.8	27.4	28.5	17.0		19.0		36.0	
Fuel consumption [3] (ton)	2.43	1.42	1.36	1.00	0.66	0.46	0.84	0.37	0.92	0.51
Max. temperature [4] (°C)	1005	897	984	953	1026	1081	1080	1010	1055	1010
Total burning time (h)	5.55	5.14	4.26	3.57	2.97	2.97	1.98	2.15	2.91	3.80

[1] Small size fuel: <10.2 cm in diameter; [2] Mixed size fuel: small size + large size (≥10.2 cm in diameter) fuel; [3] Green ton; [4] Maximum temperature of combustion zone.

Due to its higher burning efficiency, there could be a greater amount of heat released from the ACB as compared to SPB, leading to adverse impacts on soil properties. Heat produced in the ACB box can be transferred into the underlying forest floor and mineral soil by heat transfer processes such as radiation, convection, conduction, vaporization, and condensation [18], thereby changing soil physical, chemical, and biological properties. However, the spatial scale of impact may be less with an ACB than SPB because one location is used for several burns rather than numerous slash piles within one site.

In general, during woody residue burning temperatures that reach ca. 60–80 °C kill seeds, roots, and other plant tissue, even when the burn is for a short duration [19–21]. Soil temperatures reaching 100 °C can be lethal to the soil microbes [22] and temperatures ranging 200–500 °C cause reductions of soil carbon (C) and nitrogen (N), aggregate stability, and thermal conductivity [20]. While numerous studies have documented soil temperature flux during slash pile burning (e.g., [23,24]), we could find no information on soil heating while using ACB. We hypothesize that temperatures could be much higher since larger volumes of wood can be burned at once and the high turbulence associated with air movement across the burning wood can increase the chamber temperature to ≥980 °C. However, although the impacts of burning on belowground processes are highly variable [25], lack of in situ heat transfer measurements hinders the evaluation of heating damage from ACB and, perhaps, an increased use in areas with excess woody residues.

Wood ash is a byproduct of woody residue management created during burns. There has been some interest in using wood ash as a soil amendment [26]. Indeed, wood ash can return nutrients such as phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) to the soil [27] and salts in wood ash can act as a fertilizer when dissolved in the soil solution [26]. However, in large quantities, wood ash can significantly increase soil pH [28] resulting in changes in fungal populations and subsequent impacts on decomposition [29–31]. However, ash nutrient contents can be variable, depending on the burn temperature, since nutrient volatilization occurs at different temperatures [32]. Thus, we expect changes in soil nutrients, organic matter (OM), or C under an ACB might be different from those under SPB and an investigation of wood ash properties is necessary to evaluate using wood ash as a soil amendment.

Therefore, the objectives of this study were to investigate: (1) heat pulse into the mineral soil from an ACB and SPB; and (2) their effects on underlying soil properties. This study focused on disposal of forest residues resulting from thinning treatments around residential areas and city parks. For this, we tested the following hypotheses:

1. The ACB will produce a greater heat pulse and subsequently higher soil temperature profile within the mineral soil profile than SPB.
2. A greater heat pulse associated with ACB will cause larger changes in soil chemical properties as compared to SPB.
3. If the heat pulse between ACB and SPB is significant, then properties of wood ash generated by ACB would differ from those of SPB.

2. Methods

2.1. Study Sites and Burning Description

The first burning trial was conducted in the Pine Mountain Lake Association Compost Area (hereafter "Groveland") located approximately 5 km north of Groveland, California (37°51′52″ N, 120°12′33″ W). At Groveland, two kinds of fuel types were tested per burning method: small (<10.2 cm in diameter) and mixed sizes (including both large (≥10.2 cm in diameter) and small fuel) on 26 and 27 March 2017, respectively (Table 1). Fuel was from nearby landscaping and fuel treatment wastes and consisted of a mix of conifer species. On average, 1.93 and 1.18 ton (green) of fuels were consumed in small and mixed size burning trials, respectively. One gallon of diesel was used as a fire starter in each batch run in the ACB and SPB. Mixed size slash piles were constructed with an excavator and were 1.2 m in diameter and height. Slash piles from the small fuels were constructed by hand to a size similar to the excavator piles. Fuel remaining after initial SPB piling and ACB loading were manually added to the piles or ACB continuously as fuel was consumed. Both SPB and ACB were tested simultaneously. The average burning time of small-size fuel burning was 5.34 h, whereas 3.92 h for mixed-size fuel burning. Maximum temperatures of flame (measured by the ThermaCAM® SC640 IR camera (FLIR Systems, North Billerica, MA, USA) in 10-min intervals) of each burning method were 1005 °C (ACB) and 897 °C (SPB) for small fuel, whereas 984 °C (ACB) and 953 °C (SPB) were for mixed size fuel. On the days we burned, air temperature was 23.8 °C (small fuel), 20.1 °C (mixed fuel), and relative humidity was 38.1% (small fuel) and 59.2% (mixed fuel). Soil series at Groveland was a Trabuco and is classified as fine, mixed, superactive thermic Mollic Haploxeralf and has a loamy texture [33].

A second study site was near the Indian Grinding Rock State Historic Park campground (38°25′17″ N, 120°38′39″ W) and was located 3.2 km south of Volcano, California (hereafter "Volcano"). Three kinds of fuel types were tested during 13–15 June 2016: (1) cured mixed size fuel (mixture of small (<10.2 cm in diameter) and large size (≥10.2 cm in diameter) fuel); (2) (fresh) small fuel (<10.2 cm in diameter); and (3) fresh mixed size fuel (mixture of small and large size fuel). Residues for this study came from nearby ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) stands in the Park. Cured fuels were one-year-old air-dried residues created in a fuel reduction thinning. Fresh residues were drought/insect damaged or recently killed standing trees. Overall, an average of 0.66 (green) ton of fuel was burned during 2.97 h per burning trial. Measured maximum temperatures of flame for mixed size cured fuel trial were 1026 °C (ACB) and 1081 °C (SPB). For small size fresh fuel trail, 1080 °C (ACB) and 1010 °C (SPB) were the maximum flame temperature. The maximum flame temperature for mixed size fresh fuel trial were 1055 °C (ACB) and 1010 °C (SPB). Air temperatures were 30.2 °C, 24.4 °C, and 19.4 °C, and relative humidity was 35.8%, 28.7%, and 37.8% for mixed size cured, small size fresh, and mixed size fresh fuel burning trials, respectively. Soil series at Volcano was a Mariposa soil series: fine-loamy, mixed semiactive, mesic Typic Haploxerult and has a gravelly silt loam texture [33].

The BurnBoss® air curtain burner (Air Burners, Inc., Palm City, FL, USA) was used. The BurnBoss® is trailer-mounted, containing the FireBox® (combustion chamber) with 10.1 cm thick steel walls filled with thermo-ceramic materials. The bottom of FireBox® is open to the ground (i.e., bottomless), and has 3.7 m × 1.2 m × 1.2 m dimensions (L × W × H). At Volcano, we used the BurnBoss® with the ember case attached because of a high fire risk for escaping. Burning trials were conducted for a maximum 5.55 h (Groveland day 1), but we left the fire burning until the next morning to ensure complete combustion of all materials. After completion of each burning trial (both ACB and SPB), the next burning trials were conducted in different locations.

2.2. Soil and Ash Sampling

Three sampling points were assigned for each burning method. Under the ACB, we sampled in the center, and along the long- and short-edges. Under the SPB, we sampled at the center, along the edge, and halfway between the center and edge of the pile (hereafter, "midpoint"). Before and one day after each burning trial, soil samples were taken at two depths (0–10 cm and 10–20 cm) at each sample point location using a slide hammer and soil core (185 cm^3 volume) for soil property analyses. After burning, ash samples were taken from the same locations as the soil samples. Samples were sealed in the zip-type plastic bags, kept cool until shipping, and sent to Rocky Mountain Research Station (RMRS; Moscow, ID, USA) for processing and lab analyses.

2.3. Soil Heat Transfer Measurement

Before the SPB and ACB were ignited, we installed thermocouple units in each soil core sampling point. Each thermocouple unit contained six horizontally-exposed thermocouples at six soil depths (1, 2, 3, 4, 6, and 8 cm). Type K thermocouples connected to TC101A temperature data logger (MedgeTech, Warner, NH, USA) were used. Soil temperature was recorded at 5-s intervals for Groveland, but, to save memory and battery capacity, 15-s recording intervals were used at Volcano.

The burning trials lasted until combustion was complete, but we only collected temperature profiles for the first 240 min because of the limited data storage of the logger. Recorded data were aggregated into 1-min averages, and erratic measurements from data logger malfunctions were removed from further analyses.

2.4. Lab and Data Analyses

At each sampling depth, soil was analyzed for OM, C and N contents, and exchangeable cation (Ca, Mg, and K) concentrations. Before analyzing, soil samples were dried at 80 °C and all live roots and rocks were removed during sieving through 2 mm sieve. Soil samples were subsequently split, homogenized, and ground. Total C and N were analyzed with LECO-600 analyzer (LECO Corp, St. Joseph, Michigan, USA). Calcium, Mg, and K were extracted using pH neutral ammonium acetate, and measured with an atomic absorption spectrometer (Model PinAAcle 500, Perkin Elmer, Shelton, CT, USA). Total OM was measured by weight loss-on-ignition method [34] after 8-h after combustion at 375 °C. In addition, C and N concentration of the wood ash samples were measured similarly to soil samples.

Analysis of variance was conducted to detect the differences in response variables by burn method (ACB vs. SPB) and depth. For soil temperature data, peak temperature and lethal temperature duration were tested as the response variables. Lethal temperature duration was calculated through the summation of minutes over 60 °C [22,24] during the 240 min of burning. Peak temperature was log-transformed to satisfy the assumptions of model's error structure. In addition to burn method and depth, soil moisture content, fuel moisture content, and fuel type (i.e., small-fresh, mixed-fresh, and mixed-cured) were tested as the covariates. For soil properties, changes (Δ; pre-burning−post-burning) in OM, C, and N contents, and Ca, Mg, and K concentrations after burning were used as the response variables. Total burning time was added in the soil-property-test models. For ash properties, C and N contents, and Ca, Mg, and K concentration were tested. Burn method, fuel moisture, fuel type, and total burning time were included in the ash-test models. All analyses were conducted using the R statistical package [35].

3. Results

3.1. Soil Heat Transfer

At Volcano, the peak temperature (389 °C) was at 1 cm depth in the cured mixed-size fuel SPB. Data from the 1 cm depth under the ACB were lost due to mechanical malfunction. However, it is likely the 1 cm depth ACB temperature would be similar to the SPB with a similar fuel since the peak temperature at 2 cm depth reached 315.6 °C. Highest peak temperatures were recorded at the midpoint and long-edge locations of SPB and ACB, respectively. Both sites' average peak temperature of all three sample locations at 1 cm depth for ACB was 133.2 °C, whereas it was 162.2 °C for SPB (Figure 2; overall average of ACB and SPB: 147.7 °C). As expected, the temperature pulse decreased with increase of soil depth and average peak temperatures at 8 cm depth were 81.8 °C and 78.0 °C for ACB and SPB, respectively.

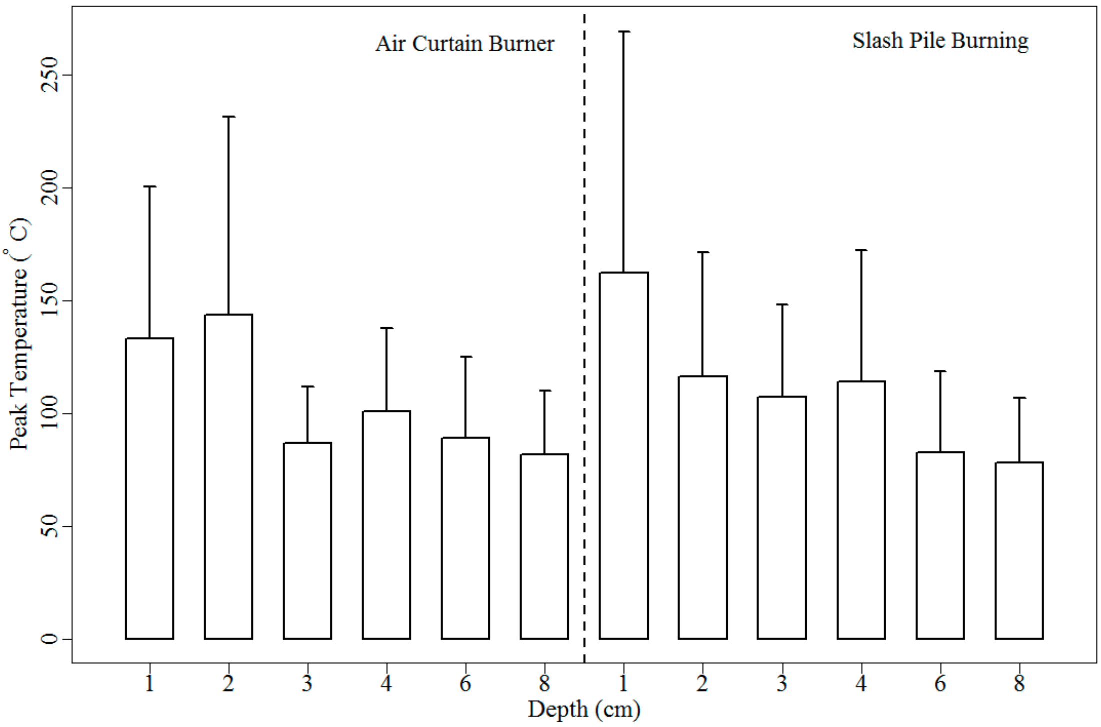

Figure 2. Mean peak temperature by soil depth. Error bars represent one standard deviation.

The result of analysis of variance indicated that there was no significant difference in peak temperature between ACB and SPB (p = 0.446) (Table 2). However, significant differences were detected by soil depth ($p < 0.001$) and soil moisture content ($p < 0.001$). The coefficient for soil depth indicated that peak temperature decreased by 7.8% for 1 cm increase in soil depth. A 1% increase in soil moisture content was associated with 4.9% decrease in peak temperature. Other covariates (i.e., fuel moisture content and fuel type) were not significantly correlated with peak temperature.

Table 2. Test results of analysis of variance for peak temperature and lethal temperature duration.

Model/Source	d.f.	MS	*F*-Statistic	*p*-Value
Peak temperature [1,2]				
Burn method	1	0.0765	0.585	0.446
Depth	1	5.0555	38.647	<0.001
Soil moisture	1	4.1666	31.851	<0.001
Lethal temperature duration [2]				
Burn method	1	7178	1.819	0.180
Depth	1	183,170	46.407	<0.001
Soil moisture	1	85,878	21.758	<0.001

[1] Log-transformed; [2] non-significant variables (i.e., fuel moisture content and fuel type) were excluded in the model.

Lethal temperature duration exhibited similar results with peak temperature (Figure 3). As expected, the maximum lethal temperature duration was observed at the 1 cm depth and occurred at the SPB midpoint location (range: 200–235 min out of 240 min) and it was consistent to the results of peak temperature. The average lethal temperature duration of all locations under the SPB occurred at 1 cm depth and lasted for 191 min. At 8 cm depth, lethal temperature lasted for only 89 min. Approximately 25% of all temperature measurements across both burning methods had no lethal temperatures at 8 cm depth.

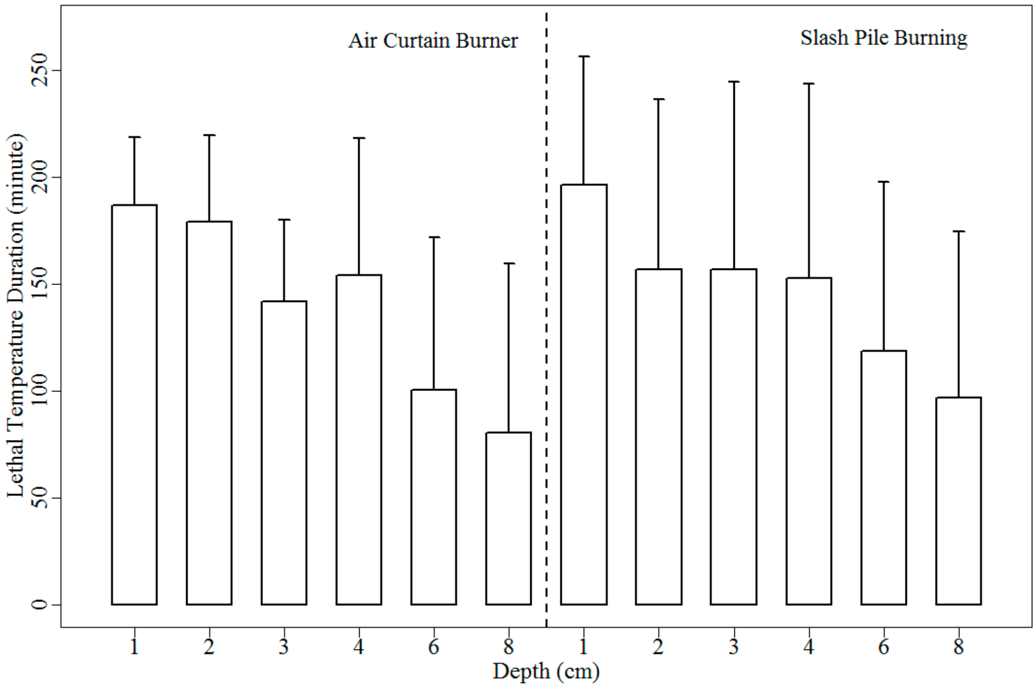

Figure 3. Mean lethal temperature duration by soil depth. Error bars represent one standard deviation.

The analysis of variance of lethal temperature yielded a similar result as peak temperature (Table 2). Burning method (SPB vs. ACB) did not affect the duration of lethal temperature ($p = 0.180$). As soil depth increased, lethal temperature duration was significantly shorter ($p < 0.001$): for each 1 cm depth increment increase, the lethal temperature duration was reduced by approximately 15.3 min. Similar to the result of peak temperature, only soil moisture content was significantly associated with the lethal temperature duration among the tested covariates ($p < 0.001$). The estimated coefficient indicated that 1% increases in soil moisture content was related with 7.3 min decrease in the lethal temperature duration.

3.2. Change in Soil Properties

In general, Volcano had lower nutrient contents than Groveland (Table 3). In particular, N contents at Volcano was quite low: only 3.3% the level of Groveland. Groveland had 64% and 43% higher OM and C contents than Volcano. Cation concentrations were consistent: Groveland's soil contained 114%, 363%, and 488% more Ca, Mg, and K as compared to Volcano's soil.

Across all soil properties, burning method appeared not to result in any notable changes except K concentration (Table 4). The average of OM contents did not change at the level of 81 Mg ha^{-1} by burnings, and reductions of OM contents were found only at 0–10 cm depth of SPB in Groveland and ACB in Volcano. However, we could not find any statistical evidence for the effects of burning method on the changes in OM contents ($p = 0.485$). In addition, none of the other covariates were associated with the changes in OM contents after burning trials. The tests for changes in C and N contents yielded the same results with OM.

Table 3. Average change from pre-burn to post burn in soil chemical properties at two soil depths in the mineral soil and C and N concentration of ash samples. Values in parentheses are the standard error (n = 18 for each burning trial).

Properties	Depth (cm)	Groveland				Volcano			
		Air Curtain Burner		Slash Pile Burning		Air Curtain Burning		Slash Pile Burning	
		Pre-Burn	Post-Burn	Pre-Burn	Post-Burn	Pre-Burn	Post-Burn	Pre-Burn	Post-Burn
OM contents (Mg ha^{-1})	0–10	94.9 (4.2)	102.8 (5.2)	125.7 (4.4)	114.3 (2.9)	94.9 (11.2)	56.1 (5.5)	50.4 (4.5)	58.7 (5.0)
	10–20	83.5 (5.1)	87.0 (5.3)	109.9 (4.6)	125.3 (5.0)	57.7 (4.8)	75.6 (6.5)	57.7 (4.5)	63.5 (4.5)
C contents (Mg ha^{-1})	0–10	76.5 (3.8)	88.2 (4.5)	97.6 (3.9)	99.1 (3.2)	70.1 (6.5)	63.5 (4.8)	49.4 (3.0)	56.7 (3.9)
	10–20	76.0 (4.4)	78.2 (3.5)	96.7 (3.3)	112.3 (4.6)	61.0 (4.3)	85.0 (6.4)	58.5 (3.8)	63.1 (3.2)
N contents (kg ha^{-1})	0–10	690 (697)	923 (845)	1568 (618)	1374 (599)	41 (290)	133 (551)	57 (403)	0 (n.a.)
	10–20	564 (669)	572 (726)	1027 (809)	1518 (652)	0 (n.a.)	43 (360)	0 (n.a.)	0 (n.a.)
Ca concentration (mg/kg)	0–10	2524 (31)	2599 (35)	5373 (36)	5567 (37)	4770 (54)	4539 (53)	2738 (33)	2618 (39)
	10–20	2321 (35)	2021 (32)	3987 (48)	4614 (35)	3231 (41)	3884 (56)	1753 (26)	1797 (28)
Mg concentration (mg/kg)	0–10	251 (11)	215 (9)	398 (7)	417 (8)	99 (6)	126 (8)	67 (6)	68 (6)
	10–20	197 (10)	180 (9)	337 (11)	374 (7)	83 (8)	113 (9)	47 (5)	49 (5)
K concentration (mg/kg)	0–10	376 (16)	429 (16)	931 (16)	867 (12)	112 (8)	152 (9)	145 (9)	135 (9)
	10–20	375 (16)	378 (16)	950 (24)	721 (12)	115 (6)	145 (10)	118 (7)	108 (8)
C concentration in ash (%)	-	-	30.3 (4.6)	-	35.3 (3.4)	-	51.6 (4.6)	-	65.6 (3.8)
N concentration in ash (%)	-	-	0.29 (0.30)	-	0.29 (0.32)	-	0.40 (0.37)	-	0.47 (0.26)
Ca concentration in ash (mg/kg)	-	-	9333 (31)	-	12187 (31)	-	13221 (60)	-	9566 (51)
Mg concentration in ash (mg/kg)	-	-	3471 (44)	-	5364 (40)	-	8080 (68)	-	3356 (47)
K concentration in ash (mg/kg)	-	-	4376 (14)	-	16125 (71)	-	27338 (113)	-	8594 (83)

Table 4. Test results of analysis of variance for soil properties. Numbers represent the *p*-values and significant results were marked in bold fonts ($p < 0.05$).

Property change (Δ)	Burn Method	Depth	Soil Moisture	Fuel Moisture	Fuel Type	Burn Time
OM contents (Mg ha^{-1})	0.485	0.112	0.708	0.817	0.837	0.275
C contents (Mg ha^{-1})	0.862	0.127	0.862	0.995	0.353	0.784
N contents (kg ha^{-1})	0.599	0.289	0.469	0.937	0.175	0.482
Ca concentration (mg/kg)	0.706	0.328	0.246	0.326	0.077	0.957
Mg concentration (mg/kg)	0.678	0.436	**0.013**	0.564	0.921	0.198
K concentration (mg/kg)	**0.009**	0.214	**0.001**	0.619	0.186	0.776

Overall average pre-burning Ca, Mg, and K concentrations were 3404.0 mg kg^{-1} (SE = 45.7), 176.7 mg kg^{-1} (SE = 11.5), and 346.2 mg kg^{-1} (SE = 17.5), respectively (Table 2). After burning, they were 3391.4 mg kg^{-1} (SE = 43.7), 181.0 mg kg^{-1} (SE = 12.2), and 408.7 mg kg^{-1} (SE = 20.9), respectively. Among the measured cations, only K was affected by the burning method ($p = 0.009$; Table 4). The SPB retained more K than ACB by 121.2 mg kg^{-1} in the soil after burning trial. Soil moisture content was positively associated with the changes in Mg (coefficient = 5.3) and K (coefficient = 21.4) concentrations. However, Ca concentration change was affected by none of the tested factors.

Average C concentration in ash generated from ACB and SPB burns were 30.3% (Groveland; ACB), 51.5% (Volcano; ACB), 35.3% (Groveland; SPB), and 65.5% (Volcano; SPB) (Table 2). Average Ca concentration of ash for ACB and SPB across all burning trials were 11,666 (SE = 58) and 10,614 (SE = 49) mg kg^{-1}, indicating a similar level between two burning methods ($p = 0.292$; Table 5). In addition, Mg concentration in the ash was did not differ by burning method (ACB: 6105 (SE = 66) mg kg^{-1}, SPB: 4159 (SE = 46) mg kg^{-1}; $p = 0.678$). Contrary to the other cations in the wood ash, K concentration from the ACB was 21,597 (SE = 123) mg kg^{-1}, which was significantly higher than SPB (10,911 (SE = 85) mg kg^{-1}; $p = 0.020$). Fuel moisture and fuel type were not associated with any of ash properties. Total burning time was a significant factor for the C and N concentration in the ash. An additional 1 h of burning time reduced 9.5% and 0.06% of C and N concentration, respectively.

Table 5. Test results of analysis of variance for ash properties. Numbers represent the *p*-values and significant results were marked in bold fonts ($p < 0.05$).

Property	Burn Method	Fuel Moisture	Fuel Type	Burn Time
C concentration (%)	0.119	0.188	0.122	**0.002**
N concentration (%)	0.289	0.126	0.257	**0.009**
Ca concentration (mg/kg)	0.292	0.191	0.112	0.074
Mg concentration (mg/kg)	0.116	0.553	0.103	0.221
K concentration (mg/kg)	**0.020**	0.726	0.054	0.162

4. Discussion

As a byproduct of harvesting or thinning activities for various objectives including restoration or stand density reduction, increasing amount of forest residues are being produced and piled in the western United State forests [36]. One of the simple disposal methods is burning; however, its impacts on soil health and productivity vary from temporary to long-term soil damage due to many factors such as soil characteristics, fuel distribution, piling method, and species composition [36]. However, our knowledge of the ecological consequences of the soil damages is still limited [37]. Since the coverage of piled woody residues could reach up to 30% of thinning units on some sites in California [38], a detrimental soil impact can lead to not only substantial economic costs but also ecological damages. Thus, investigation of soil heat transfers and subsequent changes in soil properties are required to evaluate the potential adverse impacts on soil health and productivity.

The measured soil properties in this study play the important roles in addressing soil health and productivity. Soil OM provides various essential functions such as supporting soil C cycling, regulating N and water availability, and supporting biodiversity [39,40]. Soil C is a major element of OM. Soil N is generally the most important limiting nutrient of plant growth in forests [41,42]. The cations are also the elements consisting of the body of plant, and the amount of those cations can also indicate the degree of fertility and health of soil (i.e., cation exchange capacity) [43].

Findings of this study indicate that there was not enough evidence to support the hypothesis that ACB generates greater heat pulse than SPB as there were no notable differences in temperature profiles or soil chemical properties between two burn methods. Both ACB and SPB burns maintained the maximum temperature that wood fuel combustion can reach approximately 1027–1100 °C [44,45] when there is a continuous fuel and the optimum fuel configuration for efficient combustion. Therefore, since the heat generated did not significantly alter soil quality using these burning methods, heat duration, including smoldering phase, may be an underlying cause of soil change. The ACB can consume fuels more efficiently [46] than SPB. Furthermore, because of air quality requirements and proximity to local communities, woody residue burning is often conducted on a small scale making the ACB a reasonable option to manage forest woody residues in many regions.

Continuously supplying fuel to the ACB and SPB resulted in elevated soil temperatures at the long-edge of ACB and midpoint of SPB. As operation proceeded, added fuels were more likely placed to the long-edges of the ACB. This fuel addition method is also supported by the result that high peak temperatures were observed by the thermocouples along the long-edge of the ACB, primarily at Volcano. At Volcano, we also used the ACB with the ember screening cover so that the fuel was inserted only through the slot located in the center of ACB. Therefore, the fuel supplying personnel threw fuels preferably toward the long-edge side so the fuel in the center was not stacked and did not block the feeding entrance. Similarly, in SPB, fuels are more likely stacked at midpoint, because the radiated heat made it difficult to approach the burning pile.

The majority of heat generated by fire is transferred to upward into the atmosphere by radiation, convection, and mass transfer along with smoke, gases, and particular matters [47]. Thus, only limited heat (approximately 10–15%) is estimated to be transferred into the soil by radiation [18]. In addition, since soil is not a good heat conductor [20], elevated soil temperatures near surface diminished rapidly with increasing soil depth [18]. Hartford and Frandsen [48] suggested that the soil temperature rarely exceeds 80 °C at 4 cm depth, while surface layer temperature reach 300–500 °C. This study demonstrated a consistent outcome with those assertions: a moderate heat transfer to deeper soil layer while maintaining the maximum temperatures for wood combustion aboveground (Figure 3). However, heat transfer can vary with multiple factors such as fuel characteristics, weather conditions, fire behavior, and soil properties [22,47]. Thus, more experimental replicates with a wider range of environmental conditions are essential to understand the rate of temperature reduction with soil depth.

Fire duration can also play an important role; long-duration fires caused by smoldering or heavily-loaded SPB can transfer substantial heat to belowground. Busse et al. [24] mimicked broadcast burning after mastication and reported the maximum soil surface temperatures reached 500–600 °C (dry soil) and 400–500 °C (wet soil), and observed peak temperatures at 10 cm ranged 40–105 °C. Neary et al. [22] also observed severe soil heating; 700 °C at surface over 250 °C at 10 cm depth, and greater than 100 °C at 22 cm depth. In the extreme, soil heating has been observed 1.36 m deep under heavy slash pile [23]. Thus, to minimize possible adverse impact of soil heating, the duration of aboveground combustion, including smoldering phase, should be minimized.

Fire acts to reduce the chemical elements and physical condition of the wood [49]. Heat reduces the amount of nutrients and OM through volatilization and combustion. There have been abundant reports concerning how intensive fires, such as SPB, reduces OM contents (e.g., [44,50–53]). Even at low temperatures (<100 °C), losses of soil OM may occur [22,47,49]. As temperature increased, sensitive functional groups such as phenolic OH groups and COOH groups were eliminated [54]. Thus, high heat pulse can consume OM in the soil layer, resulting in the decrease of soil OM [6]. However, increased soil OM in mineral soil layer has also been observed, mainly due to the redistribution of OM from forest floor or slash [55,56]. In addition, soil texture and soil moisture content can affect the soil chemical properties after burning [36].

In general, soil N decreases after burning. Fire scars in Arizona that were created by heavily-loaded SPB, had a significant reduction in total N [6]. Therefore, if a burning operation is conducted on soil where long-term degradation is a concern, then forest managers might have to pay attention to how slash is burned so that N losses are minimized. However, fire can transform many chemical elements, including N, to more available forms for plants or organisms [49]. Fire causes an immediate increase in ammonium ions (NH_4^+), a readily available form of N through mineralization [57,58]. In addition, favorable microenvironments (e.g., elevated nutrient, improved soil microclimate, and increased pH) increase N-fixation [40]. Wan et al. [59] support the argument that there is a significant decrease of fuel N and an increase in NH_4 and NO_3. However, the post-fire pulse of available N quickly returns to pre-burning levels, or lower, with immobilization as C:N ratio increases or through leaching if OM is lost [56]. Soil N responses to fire emphasize the importance of encouraging native vegetation recovery immediately after SPB.

Extractable cations such as Ca, Mg, and K have been known to increase after burning due the oxidation of surface OM (e.g., [51,60]). However, results from this study failed to find supporting evidence for increases in those cation concentrations. Because all of burning trails were conducted on the bare grounds with exposed mineral soil surface, thus there likely was not enough surface OM to induce any significant changes in these nutrients. In addition, the lack of significant differences may have been due to high variability of cations or an insufficient number of samples.

Wood ash applications have been considered as a potential soil amendment for both forest and agricultural sites [26,61]. Not only can wood ash neutralize soil acidity [62], it can also provide nutrients, including C, N, Mg, Ca, K, and P, to the mineral soil [63]. However, the degree and extent of the nutrient changes are related to burn temperature. For example, the C and K concentration in ash decreases as burn temperature increases [63,64]. Thus, the outcome for ash chemical concentrations in our study may be partially supported by the fact that soil heating under ACB and SPB were not significantly different. Difference in soil C and N concentrations at our two locations indicated that they were likely affected by the interaction of other factors such as fuel type (i.e., tree species), fuel moisture condition, and weather condition. Although there is little empirical evidence in the literature [26] that C and N contents in ash increased site productivity, there is evidence that it can act as a fertilizer source or to increase soil pH in acidic soils [65]. Moreover, the abundant cation concentration in wood ash can play a critical role in compensating for the loss of mineral nutrients by burning, if needed. Thus, we recommend using wood ash created in ACB as a soil amendment, especially on the sites with substantial nutrient deficiencies.

5. Conclusions and Management Implications

In this study, we compared differences in heat transfer and subsequent changes in soil properties between ACB and SPB. Our experimental trials displayed the results that there were no significant impacts of different burning methods on peak temperature and lethal temperature duration. Accordingly, we could not find any substantial changes in soil chemical properties except K concentration. This effect on K concentration was also observed in the analysis of ash properties. However, other wood ash properties were not affected by the burning methods. There was not enough evidence for the different effects on soil heat transfer and soil properties between the two different burning methods. Rather, the results indicate that the soil moisture content is a key factor for heat transfer and soil property changes.

North American, especially western USA, forest managers are now facing challenges of managing increased woody residues generated from harvesting such as fuel reduction treatments, salvage logging from wildfire and insect outbreak, or other diverse restoration efforts. Utilization of woody biomass for bioenergy or other by-products still has many constraints. Thus, it is expected that burning disposal methods will be commonly adopted in many forests to reduce potential environmental hazards. However, each burning method has its own disadvantages and they may also cause other environmental or safety issues. Therefore, forest managers should determine the advantages and limitations of each burning method when deciding on which method to use based on site and wood biomass volume. This study investigated the heat flux into the soil from ACB and SPB and subsequent changes in soil properties. Our results suggest that:

1. Since both ACB and SPB produce high burn temperatures close to the maximum for wood combustion, it is important to shorten the burn duration to prevent potential adverse ecological consequences associated with excessive heat. In terms of burning duration for a given amount of fuel, ACB is preferred to SPB because ACB has higher productivity than SPB.
2. Wet and/or high OM content soils can provide some ameliorative qualities for reducing negative impacts of heat as compared to dry or low OM content soils. Thus, burning after rain over the ground with duff layer is recommended.
3. If we extend our results to other sites, cold or arid regions may need to do post-burning amendments to provide for immediate vegetation recovery.
4. Using wood ash as a fertilizer can ameliorate some potential negative impacts of burning on the mineral soil.

This study determined there were no significant differences between ACB and SPB on two forest–urban interface sites in northern CA, USA, but may be limited in scope since the replicates of experiment were lacking due to high monetary and time costs, and limitations by logistics and regulation. In addition, our trials were conducted on bare mineral soil where the surface was highly disturbed and compacted. Thus, our result may not be consistent with other trials conducted on less disturbed forest soil where an intact forest floor is present. Further studies with additional replicates that encompass a wider range of soil and fuel conditions are required.

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