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Research Note

The relationship of post-fire white ash cover to surface fuel consumption

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Abstract. White ash results from the complete combustion of surface fuels, making it a logically simple retrospective indicator of surface fuel consumption. However, the strength of this relationship has been neither tested nor adequately demonstrated with field measurements. We measured surface fuel loads and cover fractions of white ash and four other surface materials (green vegetation, brown non-photosynthetic vegetation, black char and mineral soil) immediately before and after eight prescribed fires in four disparate fuelbed types: boreal forest floor, mixed conifer woody slash, mixed conifer understorey and longleaf pine understorey. We hypothesised that increased white ash cover should correlate significantly to surface fuel consumption. To test this hypothesis, we correlated field measures of surface fuel consumption with field measures of surface cover change. Across all four fuelbed types, we found increased white ash cover to be the only measure of surface cover change that correlated significantly to surface fuel consumption, supporting our hypothesis. We conclude that white ash load calculated from immediate post-fire measurements of white ash cover, depth and density may provide an even more accurate proxy for surface fuel consumption, and furthermore a more physically based indicator of fire severity that could be incorporated into rapid response, retrospective wildfire assessments.

Additional keywords: black char, fire effects, fire severity, fuelbed, prescribed fire.

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Introduction

Ash is the first-order fire effect that results from the near-complete combustion of fuel (Smith and Hudak 2005). Ash often appears grey when it is a mixture of white ash, the product of complete combustion (Stronach and McNaughton 1989), and black char (sometimes termed 'black ash'), the residual product of incomplete combustion (Robinson 1991). The immediate post-fire landscape is typically dominated by black char with a minor cover fraction of white ash that is difficult to quantify remotely but is readily apparent on the ground immediately post-fire (Smith and Hudak 2005). Large patches of white ash often indicate downed woody debris consumed by the fire (i.e. ghost logs). Deep white ash deposits can indicate localised severe fire effects with ecological implications, such as thermally altered soils (Goforth *et al.* 2005). Smith and Hudak (2005) proposed that the percentage of white ash cover could be considered a landscape-level indicator of downed woody debris combusted that would, when considered with biomass combustion properties, improve estimates of pyrogenic emissions (Jenkins *et al.* 1998).

In this paper, we consider fire severity only in the context of fuel consumption. Our hypothesis is that white ash cover provides a useful retrospective indicator of surface fuel consumption. To test this hypothesis, we correlate field measures of surface fuel consumption with field measures of surface cover *change* at eight experimental prescribed fires conducted from 2008 to 2010 in four fuelbed types.

Methods

Prescribed fires

Eight prescribed burns in four fuelbed types were monitored for surface fuel consumption and surface cover change. The four fuelbed types represented include: (1) *boreal forest floor* with a deep duff layer; (2) *mixed conifer woody slash* following a harvest cut; (3) *mixed conifer understorey* where fire has been excluded and (4) *longleaf pine understorey* managed with frequent fires. The *boreal forest floor* unit (97 ha) was the site of a prescribed fire experiment on 17 June 2009 at Nenana Ridge (64°37′43.126″N, 148°42′44.742″W) in interior Alaska,

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designed to test the ability of canopy fuel treatments to slow an advancing crown fire in boreal forest. Two mixed conifer forest units situated <2 km apart but with very different fuelbeds were simultaneously burned on 14 October 2010 on the University of Idaho Experimental Forest (46°50′34.299″N, 116°46′57.141″W) in north central Idaho. The *mixed conifer woody slash* unit (2 ha) was a leave tree harvest cut two years previous on a comparatively moist eastern aspect; the prescribed fire objective was to reduce hazardous fuel loads of heavy woody slash. The *mixed conifer understorey* unit (11 ha) was on a comparatively dry south-western aspect; the prescribed fire objective was to reintroduce surface fires into this unlogged forest and reduce surface fuel loads. Five *longleaf pine understorey* units (38–1147 ha) were burned: two (1–2 March 2008) at Eglin Air Force Base (30°35′24.769″N, 86°30′27.157″W) in the Florida panhandle, and three (3 and 5–6 March 2008) at Joseph Jones Ecological Research Center (31°13′58.260″N, 84°26′25.509″W) in south-western Georgia. The prescribed fire objective was to maintain longleaf pine ecosystem structure and function by burning every 1–3 years (Mitchell *et al.* 2006). All of these fires were conducted within prescribed fuel moisture and weather conditions. Hence, observed variability in fire behaviour and resulting fire effects was not noticeably influenced by topography or fire weather but by local variability in fuels, the variable of interest.

Field sampling

Surface cover fractions of green vegetation, brown non-photosynthetic vegetation (NPV), black char, white ash and soil were visually estimated before and after the prescribed burns at all the sites by the same 1–2 trained observers. Cover fractions were forced to sum to unity within 1 × 1-m plots co-located with the post-fire fuel sampling locations, as per Lewis *et al.* (2011). Pre- and post-fire sampling of surface fuels followed the protocols of Ottmar and Vihnanek (1998) and Ottmar *et al.* (1998, 2003) but necessarily differed between the four different fuelbed types sampled as summarised below.

Boreal forest floor

Surface fuels were measured in plots distributed at 30-m intervals in a systematic grid inside a 2.4-ha thinned treatment unit and immediately adjacent in unthinned forest with twice the tree density; thinned trees were carried off site so as not to contribute to surface fuel loads. Forest floor consumption was calculated as the mean of change in the forest floor depths at sixteen duff pins placed at 0.5-m intervals at each plot location and clipped flush with the moss surface (Beaufait *et al.* 1977). Depth of burn was measured from the top of the pin to the forest floor surface after smouldering combustion was complete, and total forest floor depth was measured from the top of the pin to mineral soil. Total forest floor loading and consumption were calculated by multiplying the pre-fire depth and depth reduction by an average bulk density for each forest floor horizon (Ottmar and Vihnanek 1998). Other surface fuel components (i.e. downed woody debris, shrubs, forbs, graminoids) were too rare to be tallied (Rupp *et al.* 2011).

Mixed conifer woody slash

Twenty plots were geolocated in a systematic grid spaced by 15-m intervals before the fire. Woody fuels and litter were cut with a chainsaw and hand clippers to the size of metal trays (0.47 m^2), placed in a tarp and weighed using a digital hanging scale. The metal tray was then placed on the soil surface and the fuelbed reconstructed atop 7.5 kg of dry quartzite sand spread evenly across the bottom of the tray to minimise conductive heating from the metal tray during the fire. At plots situated on a slope, mesh wire was used to contain the fuels on the tray and limit outside material from rolling in and corrupting the post-fire weights. Ten subsamples of 1000-h, 100-h and 10-h size classes of fuels (Lutes *et al.* 2006) were taken from the unit before the fire to calculate pre-fire dry weights. The day after the fire, the residual contents of each tray were collected to determine post-fire dry weight. Consumption was calculated by subtracting post-fire residue weight from pre-fire biomass weight.

Mixed conifer understorey

Five plots, each composed of four subplots, were randomly placed along the prevailing hillslope before the fire. A 20-m Brown's (1974) fuel transect was laid out in a random direction from each subplot to determine woody fuel loadings. The 100-h and 1000-h fuels were sampled along the full transect lines whereas 1-h and 10-h fuels were sampled along the first 3 m. Four logs >7.6 cm in diameter were randomly selected from the four transect lines, wrapped with wire while measuring pre-fire and re-measured post-fire for diameter and length reductions. Pre-fire herbaceous and shrub loadings were determined by destructively sampling within four 0.25 × 0.25-m clip subplots situated 4 m from plot centre; post-fire fuel loads were measured in the same manner at four subplots situated 2 m from plot centre. Sixteen duff pins per subplot were installed at 0.125-m intervals, with four pins radiating out from centre in each cardinal direction. Depth of burn and depth to mineral soil were measured post-fire, and pre- and post-fire loading for the litter and duff was calculated by multiplying the depth and depth reduction by average bulk densities (Ottmar *et al.* 1998), as in the boreal forest floor unit. Pre- and post-fire loadings for each fuelbed component were averaged across subplots, and the resulting plot-level means were differenced to calculate consumption.

Longleaf pine understorey

Clip plots were laid out systematically from a random position within each unit; 20 pre-fire and 20 post-fire plots were alternately situated at 10-m intervals along two parallel transects 40 m apart. Destructive sampling creates a fuels void where consumption cannot be meaningfully measured, which precludes collocation of pre-fire and post-fire clip plots. Thus, the plot configuration for sampling surface fuels allowed consumption to be quantified at only the unit level, by subtracting total post-fire loading from total pre-fire loading. Graminoids, forbs, saw palmetto, litter, cones and other downed woody debris were clipped in 1 × 1-m plots and woody shrubs and vines in 2 × 2-m plots. Because the units are frequently burned, duff is negligible and therefore was not measured.

Table 1. Pre- and post-fire surface fuel loadings and surface fuel consumption from prescribed fires in four fuelbed types

For the boreal forest floor unit, significant differences between means (s.e., standard error) of burned treated versus untreated plots are indicated by ***, $P < 0.001$

Fuelbed type	Range	Median	Mean (s.e.)
Boreal Forest Floor			
Treated ($n = 9$)			
Prefire Load (Mg ha^{-1})	182.7–215.3	189.9	195.8 (4.1)
Postfire Load (Mg ha^{-1})	153.8–202.4	181.6	181.8 (4.5)
Consumption (Mg ha^{-1})	3.3–61.5	8.6	14.0 (6.1)***
Consumption (%)	1.8–28.6	4.7	6.8 (2.8)***
Untreated ($n = 16$)			
Prefire Load (Mg ha^{-1})	171–238.9	213.9	209.2 (5.3)
Postfire Load (Mg ha^{-1})	151.9–201.6	184.4	180.3 (3.8)
Consumption (Mg ha^{-1})	11.2–75.6	24.1	28.9 (4.2)***
Consumption (%)	6.3–31.6	11.2	13.4 (1.7)***
Mixed Conifer Woody Slash ($n = 18$)			
Prefire Load (Mg ha^{-1})	48.6–375.7	116.7	138.4 (18.5)
Postfire Load (Mg ha^{-1})	0.4–80.4	8.5	20.1 (5.7)
Consumption (Mg ha^{-1})	25.9–372.1	103.6	118.3 (20.1)
Consumption (%)	29.4–99.8	92.8	81.1 (5.6)
Mixed Conifer Understorey ($n = 5$)			
Prefire Load (Mg ha^{-1})	9.1–60.2	43.2	38.4 (8.7)
Postfire Load (Mg ha^{-1})	8.5–39.2	26.9	27.9 (5.6)
Consumption (Mg ha^{-1})	0.6–22.6	5.0	10.8 (4.6)
Consumption (%)	6.6–47	15.7	23.0 (7.7)
Longleaf Pine Understorey ($n = 5$)			
Prefire Load (Mg ha^{-1})	4.5–11.6	5.6	6.8 (1.3)
Postfire Load (Mg ha^{-1})	0.7–5.9	3.8	3.4 (0.8)
Consumption (Mg ha^{-1})	1.7–5.7	3.3	3.5 (0.7)
Consumption (%)	29.9–84.2	49.4	52.4 (8.9)

Data analysis

Surface fuel consumption and surface fractional cover variables usually had distributions that were significantly non-normal based on the Shapiro–Wilk test for normality (Royston 1982, 1995), so Spearman rank correlations were used to test the strength of relationships. Lack of significant spatial autocorrelation was verified using Moran's I statistic (Cliff and Ord 1981) to guard against pseudoreplication. Non-parametric Wilcoxon rank sum tests appropriate for non-normal distributions were used to test for significant differences between treated and untreated plots at the boreal forest floor unit (Bauer 1972). All statistics were generated using freely available R software (R Core Team 2012).

Results

Surface fuel consumption

Mean absolute consumption was highest in the mixed conifer woody slash (118.3 Mg ha^{-1}), lowest in the longleaf pine understorey (3.5 Mg ha^{-1}) and intermediate in the mixed conifer understorey (10.8 Mg ha^{-1}) and boreal forest floor (treated: 14.0 Mg ha^{-1}; untreated: 28.9 Mg ha^{-1}) (Table 1). Mean relative consumption was highest in the mixed conifer woody slash (81.1%) and lowest in the boreal forest floor (treated: 6.8%; untreated: 13.4%), whereas 23.0% of the mixed conifer understorey and 52.4% of the longleaf pine understorey surface fuels were consumed (Table 1).

Surface cover change

Mean green surface vegetation cover was reduced by the fire to small or negligible amounts across all fuelbed types except for the boreal forest floor unit treated plots, where 40.4% remained (Table 2). Mean brown NPV cover decreased 65–70% in the two mixed conifer units, and decreased only 2% in the longleaf pine understorey units, yet increased in the boreal forest floor unit (treated: 25%; untreated: 62%), where scorching (but not charring) of green moss shifted it into the brown NPV cover fraction. Mean white ash cover increased from zero in all fuelbed types, with the largest increase in the mixed conifer woody slash (44.4%), less in the mixed conifer understorey (16.0%) and boreal forest floor (treated: 9.2%; untreated: 20.6%), and the smallest increase in the longleaf pine understorey (4.0%). Mean mineral soil cover increased in the mixed conifer woody slash (8.5%) and longleaf pine understorey units (8.6%), where there were measureable pre-fire cover fractions, but remained absent in the boreal forest floor unit and negligible in the mixed conifer understorey unit (Table 2).

Relationship between surface fuel consumption and surface cover change

Surface cover change was calculated as post-fire minus pre-fire percent cover so that fire-induced increases in black char, white ash and mineral soil cover would be expressed intuitively as positive numbers, and changes in green vegetation and brown

Table 2. Percentage cover fractions of five surface materials visually estimated before and after prescribed fires in four fuelbed types
For the boreal forest floor unit, significant differences between means (s.e., standard error) of burned treated versus untreated plots are indicated by ***, $P < 0.001$

Fuelbed type	Pre-fire			Post-fire		
	Range	Median	Mean (s.e.)	Range	Median	Mean (s.e.)
Boreal Forest Floor						
Treated ($n = 9$)						
Green Veg (%)	15.0–92.0	85.0	75.0 (8.4)	0.0–78.0	40.0	40.4 (9.1)***
Brown NPV (%)	8.0–85.0	15.0	25.0 (8.4)	22.0–86.0	50.0	50.3 (7.1)***
Black Char (%)	0.0–0.0	0.0	0.0 (0.0)	1.0–69.0	22.6	27.8 (7.4)***
White Ash (%)	0.0–0.0	0.0	0.0 (0.0)	0.0–30.0	5.0	9.2 (3.3)***
Mineral Soil (%)	0.0–0.0	0.0	0.0 (0.0)	0.0–0.0	0.0	0.0 (0.0)
Untreated ($n = 16$)						
Green Veg (%)	57.0–96.0	80.5	82.3 (2.7)	0.0–0.0	0.0	0.0 (0.0)***
Brown NPV (%)	4.0–43.0	19.5	17.7 (2.7)	65.0–90.0	80.0	79.6 (1.7)***
Black Char (%)	0.0–0.0	0.0	0.0 (0.0)	56.6–85.0	67.6	69.9 (2.2)***
White Ash (%)	0.0–0.0	0.0	0.0 (0.0)	10.0–35.0	20.0	20.6 (1.8)***
Mineral Soil (%)	0.0–0.0	0.0	0.0 (0.0)	0.0–0.0	0.0	0.0 (0.0)
Mixed Conifer Woody Slash ($n = 9$)						
Green Veg (%)	0.0–45.0	4.5	7.4 (3.4)	0.0–5.0	0.0	0.7 (0.6)
Brown NPV (%)	55.0–98.0	91.0	88.8 (3.4)	0.0–95.0	4.0	22.9 (13.2)
Black Char (%)	0.0–0.0	0.0	0.0 (0.0)	0.0–53.0	12.0	19.7 (5.8)
White Ash (%)	0.0–0.0	0.0	0.0 (0.0)	0.0–82.0	54.0	44.4 (10.0)
Mineral Soil (%)	0.0–12.0	2.5	3.8 (1.2)	0.0–26.0	16.0	12.3 (3.5)
Mixed Conifer Understorey ($n = 5$)						
Green Veg (%)	7.8–33.5	27.3	23.1 (4.7)	0.0–1.2	0.0	0.4 (0.3)
Brown NPV (%)	66.5–91.2	72.0	76.6 (4.6)	0.5–15.0	7.0	7.0 (2.5)
Black Char (%)	0.0–0.0	0.0	0.0 (0.0)	54.0–90.5	81.2	76.6 (6.6)
White Ash (%)	0.0–0.0	0.0	0.0 (0.0)	6.5–43.8	9.2	16.0 (7.1)
Mineral Soil (%)	0.0–1.0	0.0	0.3 (0.2)	0.0–0.5	0.0	0.1 (0.1)
Longleaf Pine Understorey ($n = 5$)						
Green Veg (%)	3.6–24.1	12.8	12.1 (3.8)	0.5–3.0	1.3	1.7 (0.5)
Brown NPV (%)	71.3–89.2	81.0	80.2 (3.3)	62.2–93.2	85.4	78.2 (6.7)
Black Char (%)	0.0–0.5	0.0	0.1 (0.1)	46.6–90.3	67.8	71.0 (7.6)
White Ash (%)	0.0–0.0	0.0	0.0 (0.0)	1.2–9.2	2.5	4.0 (1.4)
Mineral Soil (%)	2.2–21.0	4.6	7.6 (3.4)	4.3–32.6	9.4	16.2 (5.5)

NPV cover as negative numbers. Of the five surface cover change variables measured, only the changes in white ash cover were significantly correlated with either absolute or relative surface fuel consumption (Table 3). In the boreal forest floor unit, the untreated plots produced over twice as much white ash cover as the treated plots, but were much less variable (Table 2), which is why correlations with either absolute or relative surface fuel consumption were significant in treated plots but not in untreated plots (Table 3).

Discussion

Across four fuelbed types in this study, increased white ash cover was the only surface cover change measure that significantly correlated with surface fuel consumption (Table 3), which supports our hypothesis and justifies the prediction of surface fuel consumption based on post-fire white ash cover. Measures of white ash cover, depth and density would allow calculation of white ash load, which could more strongly correlate to surface fuel consumption, particularly when large downed woody fuels are consumed to leave a deep ash layer (i.e. ghost logs). Lacking white ash depth and density measures with which to calculate white ash load, we can only speculate that absolute consumption produced the significant correlation ($\rho = 0.81$) with increased white ash cover in the mixed conifer woody slash unit because it was a predominantly woody fuelbed that burned (leaving many ghost logs) whereas in the longleaf pine understorey units the paucity of woody fuels (relative to the other fuelbed types) made relative consumption the significantly correlated measure ($\rho = 1.00$).

Either white ash cover or load may be excellent indicators of fire severity on the ground but are difficult to scale up to the landscape level via remote sensing given that white ash deposits tend to be highly localised, with much smaller areal coverage relative to the black char background (Smith and Hudak 2005). Therefore, efforts to estimate ash cover remotely for the purpose of landscape-level fire severity or pyrogenic emissions assessments may require very high spatial resolution, hyper-spectral resolution, or both (Robichaud *et al.* 2007; Lewis *et al.* 2011).

We visually estimated white ash cover immediately post-fire, before charred tree residues fell to the ground or the white ash was lost to solubilisation processes due to precipitation, or by wind. Lewis *et al.* (2011), in a similar study following the 2004 Taylor Complex wildfires in interior Alaska boreal forest,

Table 3. Spearman correlations between surface fuel consumption and post-fire minus pre-fire surface cover change (%) in four fuelbed types
Significant correlations are indicated by *, $P < 0.05$

Fuelbed type	Δ Green Veg (%)	Δ Brown NPV (%)	Δ Black Char (%)	Δ White Ash (%)	Δ Mineral Soil (%)
Boreal Forest Floor					
Treated ($n = 9$)					
Consumption (Mg ha^{-1})	−0.59	0.18	0.62	0.77*	–
Consumption (%)	−0.59	0.18	0.62	0.77*	–
Untreated ($n = 16$)					
Consumption (Mg ha^{-1})	0.35	−0.40	−0.37	0.07	–
Consumption (%)	0.37	−0.45	−0.42	0.10	–
Mixed Conifer Woody Slash ($n = 8$)					
Consumption (Mg ha^{-1})	0.11	−0.69	0.21	0.81*	0.36
Consumption (%)	−0.36	−0.48	0.71	0.29	0.55
Mixed Conifer Understorey ($n = 5$)					
Consumption (Mg ha^{-1})	0.40	−0.20	−0.80	0.87*	0.41
Consumption (%)	0.40	−0.20	−0.80	0.87*	0.41
Longleaf Pine Understorey ($n = 5$)					
Consumption (Mg ha^{-1})	0.40	−0.40	0.20	0.50	0.40
Consumption (%)	0.70	−0.70	0.60	1.00*	0.70

obtained a significant Spearman correlation ($\rho = 0.80$) between post-fire white ash cover and percent forest floor consumption, based on surface cover estimates collected 6–34 days post-fire – but before any significant rain events could redistribute or remove the ash. This finding is corroborated by the Spearman correlation ($\rho = 0.77$) found at the boreal forest floor unit treated plots in this study (Table 3).

Prescribed fires facilitate spatially coincident measurements of pre-fire fuels, active-fire behaviour, fire effects and their relationships. Spatially coincident and timely measurements are necessary to parameterize and validate the next generation of physics-based fire behaviour and fire effects models (Dickinson and Ryan 2010; Kremens *et al.* 2010). Direct measures of fuel consumption are highly desirable, but the pre-fire fuel measures required to calculate consumption are rarely available, especially in wildfire situations. Therefore, retrospective indicators of fuel consumption and other first-order fire effects must often suffice. Improved methods for quantifying post-fire white ash and using it as a surrogate for fuel consumption are needed in the fuelbed types sampled in this study, as well as others.

Conclusion

Our results support our original hypothesis that increased white ash cover is significantly correlated with surface fuel consumption; no other estimates of surface cover *change* (green vegetation, brown NPV, black char or mineral soil) correlated significantly with surface fuel consumption across four very different fuelbed types (boreal forest floor, mixed conifer woody slash, mixed conifer understorey and longleaf pine understorey). Post-fire white ash cover measured before rain or wind events may provide a reliable, retrospective indicator of surface fuel consumption that should be further tested in these and other fuelbed types. An improved assessment protocol to measure post-fire white ash cover, depth and density could facilitate more accurate relationships between white ash load and surface fuel consumption. It could also help fire scientists and managers move a step closer towards more physically based definitions and assessments of fire severity.

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