Pre- and postfire surface fuel and cover measurements—RxCADRE 2008, 2011, and 2012

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Abstract. Multi-scale measurements of pre-, during, and postfire fuel and white ash variables were collected on 28 sample units associated with 6 small replicate and 10 large operational prescribed fires conducted during the RxCADRE research campaign in 2008, 2011, and 2012 in longleaf pine (*Pinus palustrus*) ecosystems of the southeastern USA. Fuel loading averaged 5.0 Mg ha^{-1} and ranged from 1.7 Mg ha^{-1} on a sparsely vegetated nonforest unit to 11.5 Mg ha^{-1} on a managed longleaf pine forest unit; fuel consumption averaged 3.2 Mg ha^{-1} and ranged from 1.1 Mg ha^{-1} to 8.5 Mg ha^{-1}. Relative consumption was generally lowest on forest units and highest on nonforest units, ranging from 30 to 93%. There were highly significant correlations between many of the fuel variables, with postfire white ash cover (ranging from 1 to 28%) and exposed mineral soil cover (ranging from 4 to 81%) producing the highest correlations with pre- and postfire surface fuel loadings and consumption. Our data reported here have not been used to develop fire models and thus can be used as an independent data set for evaluating such models. The data is available from the US Forest Service Research National Archive Data Center.

Additional keywords: fuel loading, ash, prescribed fire, fire effects

Summary for Table of Contents

We present ground-based measurements of fuel loading, fuel moisture content, fuel consumption, and surface cover fractions collected on 28 sample units associated with 16 prescribed fires in the southeastern United States as part of the RxCADRE project. Fuel loading ranged from 1.7 Mg ha^{-1} to 11.5 Mg ha^{-1}; fuel consumption ranged from 1.1 Mg ha^{-1} to 8.5 Mg ha^{-1}. Postfire white ash cover ranged from 1 to 28% and is indicative of prefire fuel loadings and surface fuel consumption. The data can be used to evaluate fire models.

Introduction

Consumption of fuel during wildland fire is the basic process that leads to heat generation and emissions, driving fire behavior, and accounting for fire effects such as smoke impacts on communities, carbon reallocation, tree mortality, and soil heating (Agee 1993; Hardy *et al.* 2001; Ottmar 2013; Parsons *et al.* in press). To assist managers in planning for wildland fire, consumption studies of shrubs, forbs, grasses, woody fuel, litter, and duff in forests and rangelands have been conducted in temperate, tropical, and boreal regions of the world and offer data sets that include fuel characteristics, fuel moisture, fuel consumption, and environmental variables from both wildfires and prescribed fires (Ottmar 2013). These datasets have been used to develop fuel consumption models in software systems in use today such as Consume (Prichard *et al.* 2007), FOFEM (Reinhardt *et al.* 1997), CanFIRE, and BORFIRE (de Groot *et al.* 2007, 2009). Although mainstays of fire effects modeling, the aforementioned modeling systems have not been quantitatively evaluated because independent, fully documented, quality-assured fuel consumption data are lacking (Alexander and Cruz 2012; Cruz and Alexander 2010). One way to acquire an independent data set is by collecting ground measurements of pre- and postfire fuel characteristics and conditions during prescribed fires (Macholz *et al.* 2010, Ottmar *et al.* 2013). Fuel consumption measurements are difficult and costly however, more efficient methods to measure fuel consumption on the ground are desirable.

One potential method to estimate surface fuel loadings and consumption retrospectively is to quantify immediate fire effects, such as the amount of residual white ash (Hudak *et al.* 2013a, 2013b). This would be especially useful in the case of wildfires, where prefire measurements are generally unavailable. Although prescribed fires do not typically produce as wide a range of fire intensity and severity as wildfires (van Wagtendonk and Lutz 2007), they do exhibit spatial and temporal variability that can be measured to advance understanding of both small-scale (0 to 10 m) and large-scale (10 to 1000 m) fire dynamics and effects. Hudak *et al.* (2013a) found that white ash cover correlates significantly to surface fuel consumption across four very different fuel types, including frequently burned longleaf pine (*Pinus palustris* Mill.) stands in the southeastern USA. They asserted that this should be expected given that white ash is the direct result of complete fuel combustion (Smith and Hudak 2005). Other studies have shown that black ash (char, the product of incomplete combustion, and white ash are good indicators of fire severity (Smith and Hudak 2005; Smith *et al.* 2007; Lentile *et al.* 2009).

This paper presents ground-based measurements of fuel loading, fuel moisture content, fuel consumption, and postfire cover fractions of white ash and other surface materials collected on 28 sample units associated with 16 experimental prescribed fires conducted at Eglin Air Force Base (Florida) and the Joseph W. Jones Ecological Research Center (Georgia) during 2008, 2011, and 2012. This data collection was part of the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE). The data can be used to evaluate fuel consumption and other fire models. In addition, we assessed whether ocularly estimated cover fractions of postfire surface materials correlate significantly to prefire fuel loading and fuel consumption. We hypothesized that white ash cover—a first-order fire effect that results from complete combustion of fuels—should strongly correlate with fuel consumption. Finally, we discuss how the strong relationships of postfire surface material cover with fuel loading and fuel consumption could be used to retrospectively estimate fuel loading and consumption at larger scales.

Methods

We measured prefire fuel characteristics by fuelbed category, fuel moisture content immediately prior to ignition, postfire fuel characteristics, and postfire surface cover fractions in 28 sample units within 6 small replicate and 10 large operational prescribed fire burn blocks in the southeastern USA in 2008 (burn block n=5; sample unit n=5), 2011 (burn block n=2; sample unit n=5), and 2012 (burn block n=9; sample unit n=18) (Fig. 1). All of the 2008 and 2011 burn blocks were forested, with longleaf pine dominating the overstory and turkey oak (*Quercus laevis* Walter) and saw palmetto (*Serenoa repens* [W.Bartram] Small) frequently occurring in an understory matrix of wiregrass (*Aristida stricta* Michx.) and other grasses (Fig. 2*a*). One 2012 burn block was a longleaf pine forest and the other eight burn blocks were nonforest with a mix of grasses, forbs, and shrubs (Fig. 2*b*). All burn blocks had been regularly prescribed burned every one to three years to meet several management objectives including fuel reduction to mitigate fire hazard, longleaf pine ecosystem and associated wildlife habitat maintenance, and keeping the site clearing for military training operations.

All burns followed established prescription criteria for meeting land management objectives; no burning occurred under extremely dry or wet conditions. Prescription parameters were: 10-hr fuel moisture 4–20%; 1000-hr fuel moisture 15%–40% and wind <8.9 m s^{-1}. In March 2008, two blocks were burned at Eglin Air Force Base (AFB) in northwestern Florida and three blocks were burned at the Joseph W. Jones Ecological Research Center at Ichauway (Jones Center) in southwestern Georgia. Destructive sample fuel plots were established in a systematic grid pattern in each 5 ha sample unit. Twenty prefire and 20 postfire fuel plots (1 m x 1 m) were alternately located at 20 m intervals along two parallel transects 40 m apart. In February 2011, two blocks at Eglin AFB were burned, with two widely separated sampling units in one burn block and three widely separated sampling units in the other. One sampling unit in the latter case had 20 prefire and 20 postfire fuel plots (1 m x 1 m) alternately situated at 5-m intervals along two parallel transects 30 m apart (similar to the 2008 sampling design). The other four sampling units each consisted of 20 prefire and 20 postfire fuel plots (1 m x 1 m) distributed at 5-m intervals around the periphery of a 40 m x 40 m highly instrumented plot (HIP). In November 2012, six small blocks (2 ha each) and three large blocks (>125 ha each, comparable in size to the 2008 and 2011 burn blocks) were burned at Eglin AFB. The small blocks were each surrounded by 25 prefire and 25 postfire fuel plots alternately situated at 10-m intervals (Fig. 3A). In each of the large blocks, 30 prefire and 30 postfire fuel plots were alternately situated at 50-m intervals along three roughly parallel transects about 100 m apart (similar to the 2008 sampling design). An additional three sampling units were located within each large block, each consisting of either 9 (two nonforest blocks) or 12 (one forest block) prefire and postfire clip plots alternately situated at 2.5-m intervals around the periphery of a 20 m x 20 m HIP (similar to the 2011 sampling design) (Fig. 3B). Clip plots in the 2012 nonforest sample units were 1 m x 1 m as in 2008 and 2011. Fuel plots in the 2012 forest sample units were 0.5 m x 0.5 m.

Fuel from within all fuel plots was collected and categorized into four fuelbed categories [herbaceous (grasses and forbs), shrub, down-and-dead wood by size class, and litter], oven dried at 70°C, then weighed to determine pre- and postfire loading. Consumption was calculated by subtracting the average prefire loading from average postfire loading, by fuelbed category, for each set of plots. Five to ten 6-liter plastic bags of fuel moisture content samples representing shrubs (stems and leaves), grasses, small and large woody material, and litter were collected immediately before each burn, weighed and oven dried at 70°C for 48 hours to determine moisture content as a fraction of dry weight.

Because of frequent burning in this longleaf pine ecosystem, little accumulation of large woody debris occurs. However, planar intersect transects 22 m long (Brown 1974) originating at each fuel plot were used to quantify woody fuels >7.6 cm in diameter in a forested block in 2008 (307B) and 2012 (L2F), the only two units where there was enough >7.6 cm diameter woody debris to measure. These 7.6-cm diameter woody fuels were measured and included in the unit-level pre- and postfire fuel loading and consumption calculations.

Surface cover fractions were estimated ocularly prior to disturbance of postfire fuel collection, under the constraint that the four cover fractions of green vegetation, litter (including dead vegetation and woody debris), white ash, and mineral soil must sum to one. Char cover was estimated outside the unity constraint and represents the combined percentage of litter and soil that was blackened by the fire.

Because pre- and postfire fuel plot locations must differ, absolute consumption (Mg ha^{-1}) and relative consumption (%) could only be calculated at the site level. Thus plot-level measurements (loading, consumption, cover) were aggregated to the site level for analysis. Owing to the non-normality of data distribution, Spearman correlations were used to test the strength of relationships between surface fuel loading or consumption measurements and surface cover fractions (%). Data analysis was performed using R statistical software (R Core Team 2012).

Results

No large prefire fuel loading or exceptional fuel consumption values were noted because all units were regularly burned every 1 to 3 years and the fires followed established prescriptions to safely maintain control and meet land management objectives. Fuel loading averaged 5.0 Mg ha^{-1} across all blocks and ranged from 1.7 Mg ha^{-1} on a nonforest site (L1G-HIP 2) at Eglin AFB to 11.5 Mg ha^{-1} on a forest site (Dubignon East) at the Jones Center (Fig. 4), where productivity is higher than at Eglin AFB. Sample site L1G-HIP 2 was sparsely vegetated with only grasses and forbs and had been burned and treated with herbicide the year prior to the 2012 RxCADRE experiment. The Dubignon East site was a longleaf pine forest with a heavy shrub component and abundant, small down and dead woody material, and litter that had been burned three years before the 2008 RxCADRE experiment.

The day-of-burn fuel moisture content of shrubs ranged from 12.2% in Dubignon East to 144.7% in S4; herbaceous fuel moistures ranged from 14.6% in 608A to 109.7% in S4 (Fig. 5). The fuel moisture content for the down-and-dead woody material less than 7.6 cm in diameter ranged from 18.5% in L2F to 61.3% in 703C-E and 703C-W; litter moisture content ranged from 8.2% on S4 to 24.9% on 703C-E and 703C-W.

Fuel consumption averaged 3.2 Mg ha^{-1} across all sample units with the lowest consumption measured on the sparsely vegetated L1G-HIP 3 nonforest site (1.1 Mg ha^{-1}) and highest on the L2F-HIP 3 forest site (8.5 Mg ha^{-1}) (Fig. 6). Higher prefire fuel loadings in the forested sites generally led to higher fuel consumption by mass than in the nonforest units. Relative consumption was generally lowest on forested sites and highest on nonforest sites, ranging from 30% (North Boundary) to 93% (L2G-HIP2) (Fig. 7).

Postfire surface cover was primarily composed of unburned litter (mean 53%, s.d. 17%) and mineral soil (mean 39%, s.d. 18%) with minor contributions of green vegetation (mean 3%, s.d. 4%) and white ash (mean 4%, s.d. 3%). Slightly less than half (mean 48%, s.d. 19%) of the litter and soil components of the postfire plots were charred. Variability between sample units was high for all cover fractions: mineral soil cover ranged from 4% to 81%, white ash cover from 1% to 28%; litter cover from 14% to 93%; green vegetation cover from 0% to 10%; and the black char fraction of the postfire plot ranged from 13% to 90% (Fig. 8).

All postfire surface cover fractions were significantly correlated with pre- and postfire fuel loadings, except green vegetation (Table 1). All cover fractions were significantly correlated with absolute consumption, but only soil cover was significantly correlated with relative consumption. White ash cover was significantly correlated with absolute consumption (Spearman's $\hat{\rho} = 0.76$, $P < 0.001$), as hypothesized, and was nearly as highly correlated with absolute prefire fuel loading ($\hat{\rho} = 0.73$, $P < 0.001$) (Table 1). Therefore, using ln-transformed data to correct for non-normality, we developed simple linear regression models using white ash cover to predict prefire fuel loading (adj. $R^2 = 0.52$) and consumption (adj. $R^2 = 0.51$); both models were highly significant ($P < 0.001$). As for which fuelbed components most influenced white ash production, we found that white ash cover was most strongly correlated to the herbaceous, woody, and litter components of the prefire fuels, and the herb and litter components of consumption (Fig. 9).

Exposed mineral soil correlated highly with fuel loading measured pre- ($\hat{\rho} = 0.79$, $P < 0.001$) and postfire ($\hat{\rho} = 0.77$, $P < 0.001$) (Table 1). However, unlike white ash, mineral soil varied highly not just after the fire (Fig. 8) but before (not shown). If the prefire soil cover fraction is subtracted from the postfire fraction to calculate fractional cover change, then the Spearman ($\hat{\rho}$) correlations with pre- and postfire fuel loadings decreased to -0.69 and -0.71, respectively. The increase in mineral soil cover caused by the fire correlates highly with relative consumption ($\hat{\rho}$ = 0.79), particularly relative consumption of the wood ($\hat{\rho}$ = 0.90) and litter ($\hat{\rho}$ = 0.92) fuelbed components. Measured pre- and postfire fuel loadings were themselves good indicators of consumption: fuel consumption was significantly correlated to prefire fuel load (Spearman's $\hat{\rho}$ = 0.83, P <0.001), especially the litter component ($\hat{\rho}$ = -0.86, P <0.001); relative fuel consumption was significantly correlated to postfire fuel loading ($\hat{\rho}$ = -0.87, P <0.001), but not to any particular fuelbed component.

Discussion

The pre- and postfire data presented in this paper have not been used to produce or modify fire models. Consequently, the data can be used to evaluate fuel, fire behavior, smoke, and fire effects models such as the Wildland-Urban Interface Fire Dynamics Simulator (WFDS) (Mell *et al.* 2007), FIRETEC (Linn *et al.* 2002), FlamMap (U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station 2014), BehavePlus (Heinsch and Andrews 2010), Consume (Prichard *et al.* 2007), FOFEM (Reinhardt et al. 1997), BlueSky Playground (Larkin *et al.* 2009), Interagency Fuels Treatment Decision Support System (JFSP (2012), CanFIRE, and BORFIRE (de Groot *et al*. 2007, 2009). Fuel loading, fuel moisture content, and fuel consumption data are also expected to be used by those in other scientific disciplines to evaluate their results within the broader RxCADRE research effort.

Prichard *et al*. (2014) compiled a large data set of prefire fuel loading and fuel consumption measurements from 43 prescribed burns in longleaf pine forests and used it to evaluate Consume (Prichard *et al.* 2007) and the First Order Fire Effects Model (Reinhardt *et al.* 1997). Although the mean and range of the prefire fuel loading and fuel consumption found in the dataset presented in this paper is less, it represents both forested and nonforested areas; we believe it is a good representation of burning in longleaf pine ecosystems and is therefore a valuable evaluation data set.

White ash cover was the postfire surface material most highly correlated to fuel consumption (Table 1). This result demonstrates the potential utility of white ash cover for retrospective estimates of fuel loading and consumption upon which emissions estimates are based (Jenkins *et al.* 1998), especially in wildfire situations where prefire fuel loading is unknown. Unfortunately, white ash is a minor cover fraction even when estimated immediately postfire as in this study, and soon dissipates (Hudak *et al.* 2007), making it difficult to assess except under optimal conditions. Other postfire surface cover fractions like black char, mineral soil, and unburned green and non-photosynthetic vegetation (NPV) that includes dead herbaceous vegetation, litter and downed woody debris are more persistent and have greater areal coverage, making them more feasible to quantify, not just on the ground but remotely. This idea of scalable variables is supported by Smith *et al.* (2007), who found black char fraction to be a good indicator of tree mortality in ponderosa pine forests. Lewis *et al.* (2011) found significant correlations between fuel consumption and postfire cover materials (green vegetation, NPV, black char, white ash, and exposed mineral soil or rock) estimated on the ground and by remote sensing at the 2004 Taylor Complex wildfires in interior Alaska. In that study, the postfire cover measure most highly correlated to fuel consumption was green vegetation (or the lack thereof), rather than black char or white ash.

This research project provided an opportunity to modify and calibrate fuel loading and fuel consumption inventory techniques on sites with a relatively flat and homogenous fuelbed. Although we used a standard sampling protocol of destructive sample plots and the planar-intersect inventory, more plots and longer transects should be considered where needed to reduce the error associated with fuel variability. The next step will be to extend this research to more complex fuelbeds with greater spatial variability. In fuelbeds with a larger component of large woody debris that are often totally combusted leaving a layer of white ash (often called ghost logs), measures of white ash depth, rather than just cover, should be considered to permit a more accurate estimate of the volume of white ash produced by the fire.

Conclusion

This paper offers a review of ground-level surface fuels data collected (loading, consumption, moisture content) during the 2008, 2011, and 2012 RxCADRE field campaigns in longleaf pine ecosystems in the southeastern United States. An assessment of surface fuel loadings and consumption and their relationship to postfire surface cover fractions is also provided. The pre- and postfire fuel loading and consumption observed in the RxCADRE experiments fell within the range found in the literature and can be used for evaluation or modification of current fuel consumption and other fire models. White ash cover measured immediately after a fire is a strong indicator of prefire fuel loading and surface fuel consumption, justifying the quantification of white ash in retrospective assessments of fuel consumption and fire severity. These and other data collected by the RxCADRE project team have been made available on a globally accessible repository maintained by the US Department of Agriculture, Forest Service Research (2014) for use in testing and evaluation of fuel, fire, and fire effects models.

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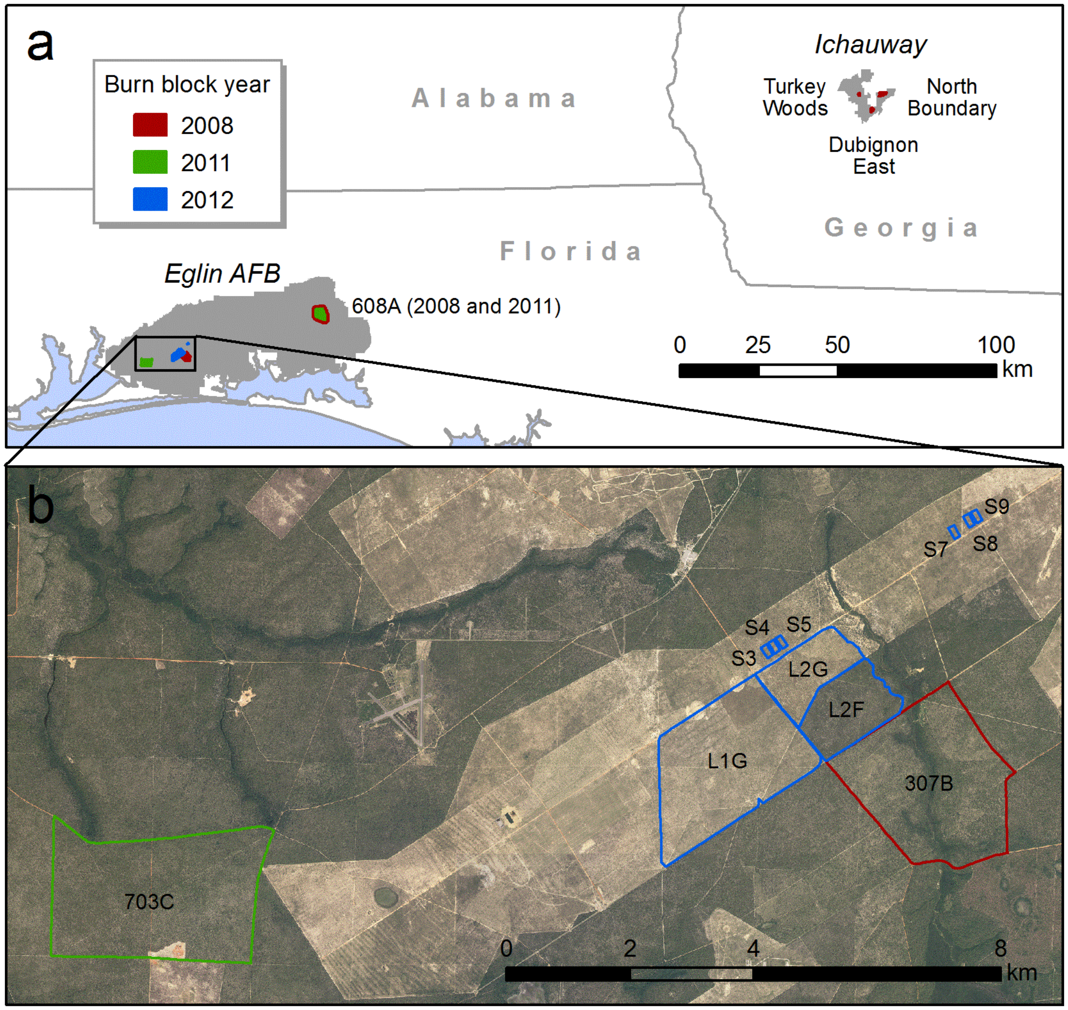

Fig. 1. (a) Location of the 16 RxCADRE experimental prescribed fires conducted in 2008, 2011 and 2012. (b) Small replicate (*S*) and large operational (*L*) burn blocks were established for the 2012 RxCADRE research project located on the B70 bombing range at Eglin Air Force Base, Florida. Only large operational burn blocks were established for the RxCADRE research burns in 2008 and 2011.

Fig. 2. (a) Typical forested and (b) nonforest blocks burned in 2012 at Eglin Air Force Base.

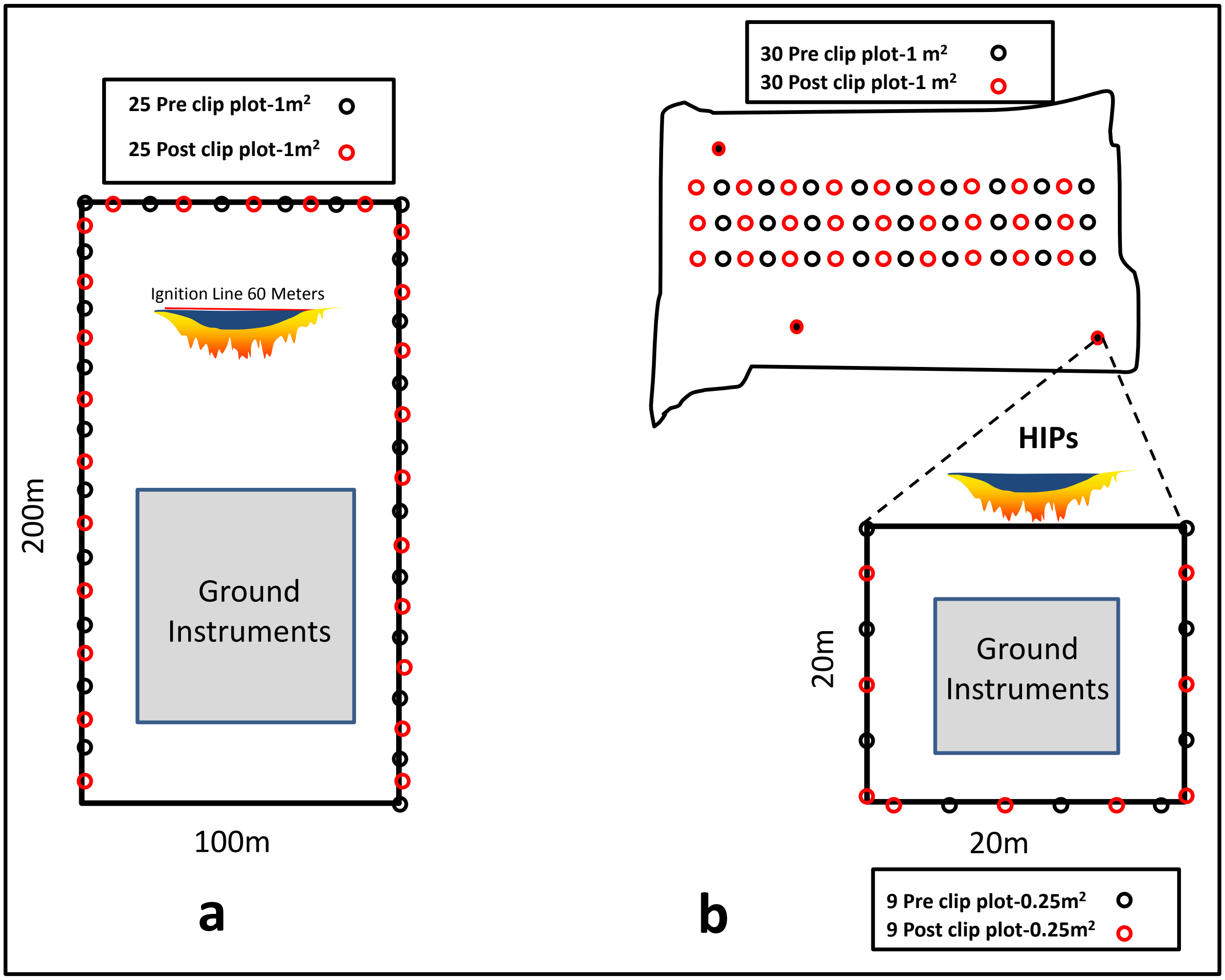

Fig. 3. Plot layout for (a) replicate experimental fire sample units, and (b) large operational burn blocks with sample units for the 2012 RxCADRE burns. Only large operational burns with one to three sample units were established in the 2008 and 2011 research burns. Surface cover fractions were estimated at the postfire clip plots.

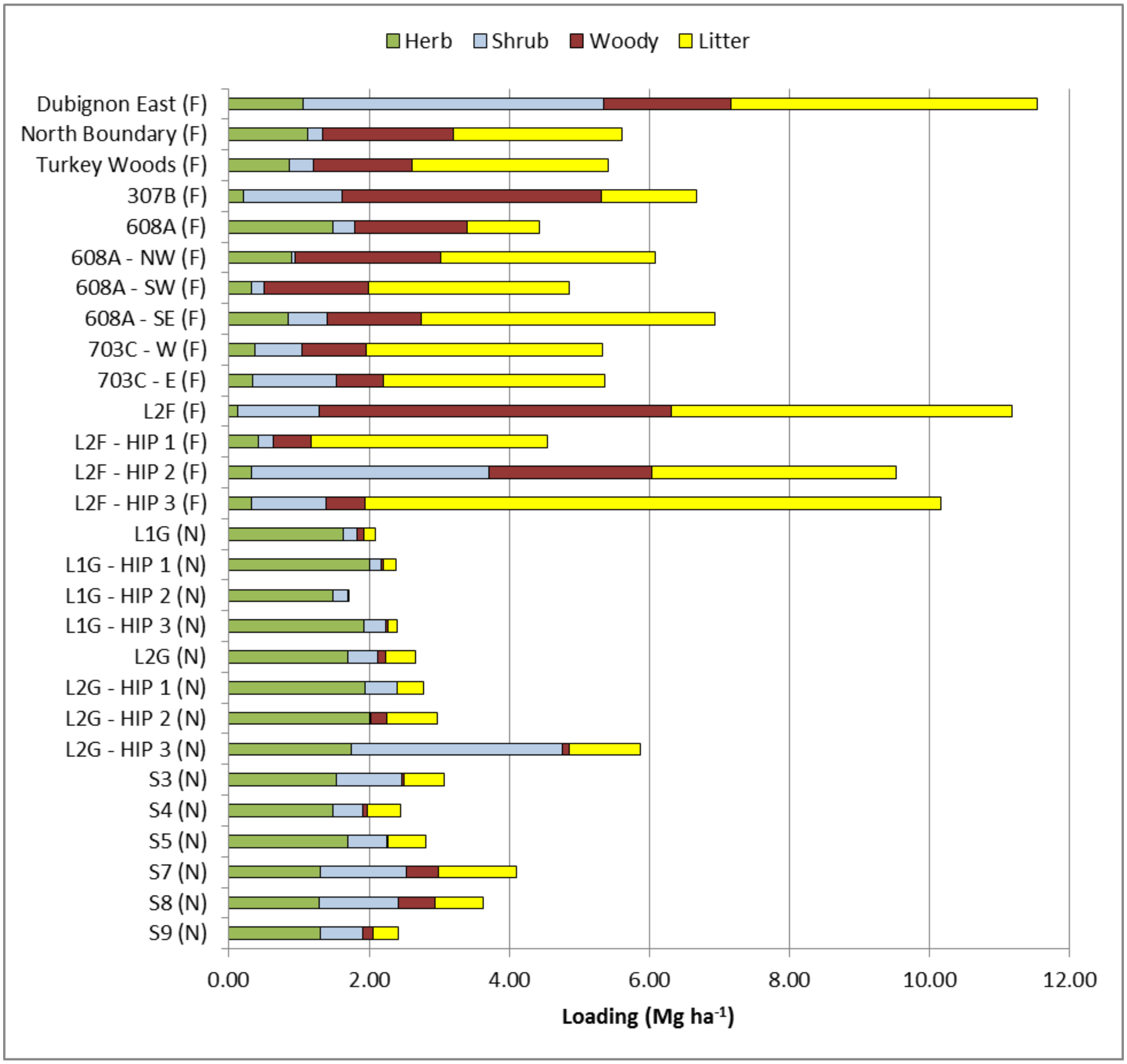

Fig. 4. Measured fuel loading by fuelbed component for forest (F) and nonforest (N) sample sites.

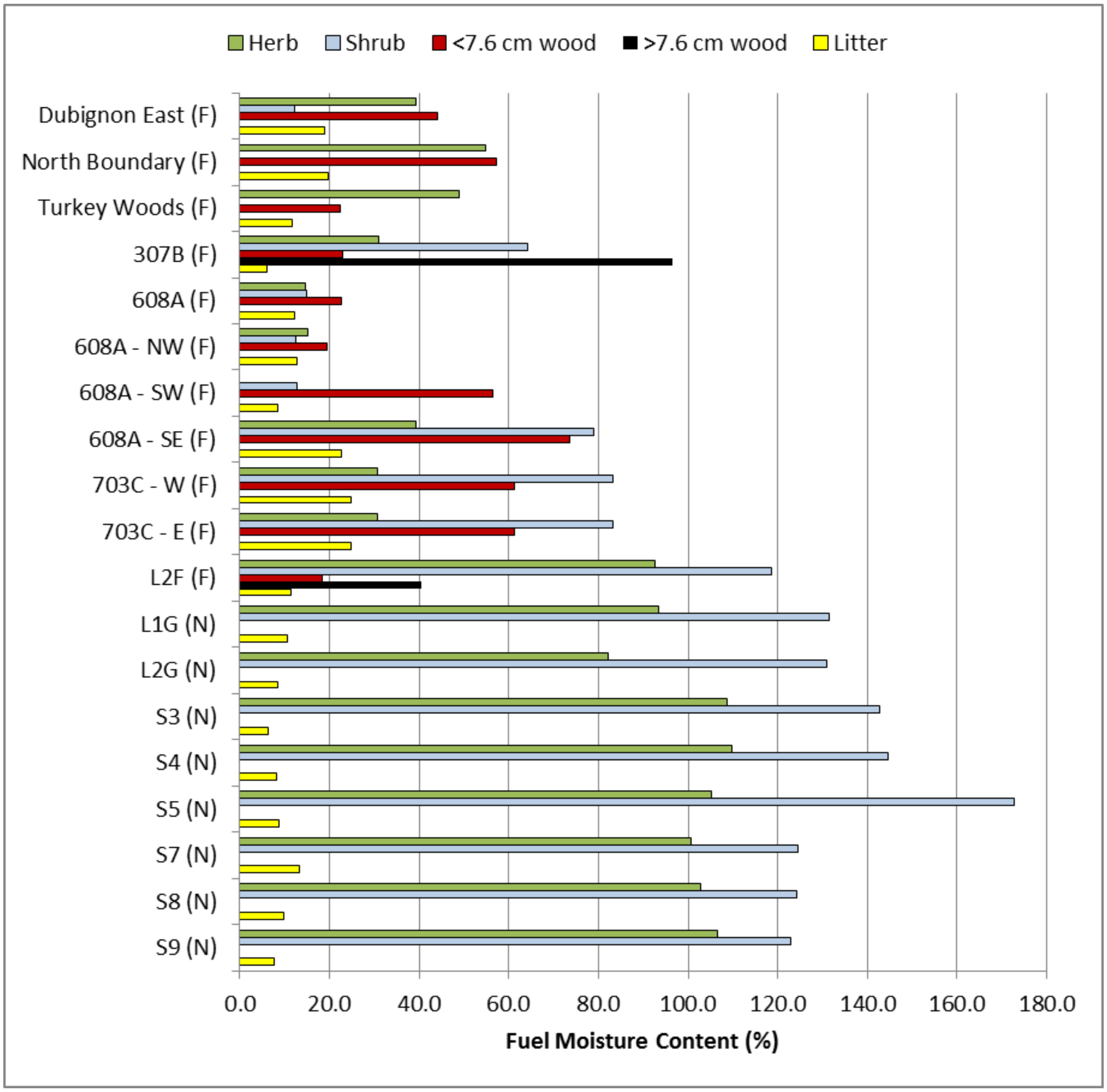

Fig. 5. Measured fuel moisture content for fuelbed components for forest (F) and nonforest (N) sample sites.

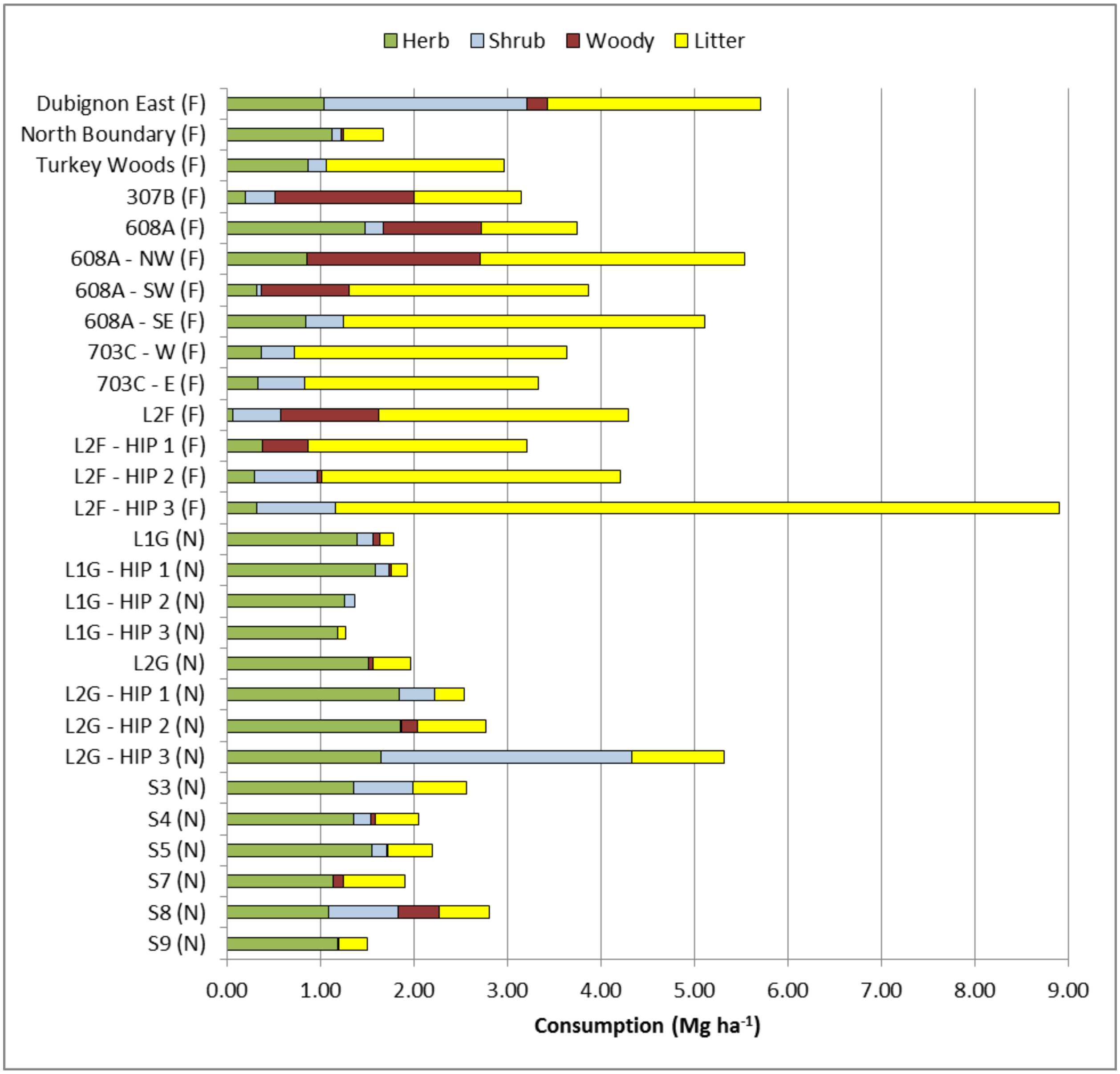

Fig. 6. Measured fuel consumption for each fuelbed component for forest (F) and nonforest (N) sample sites.

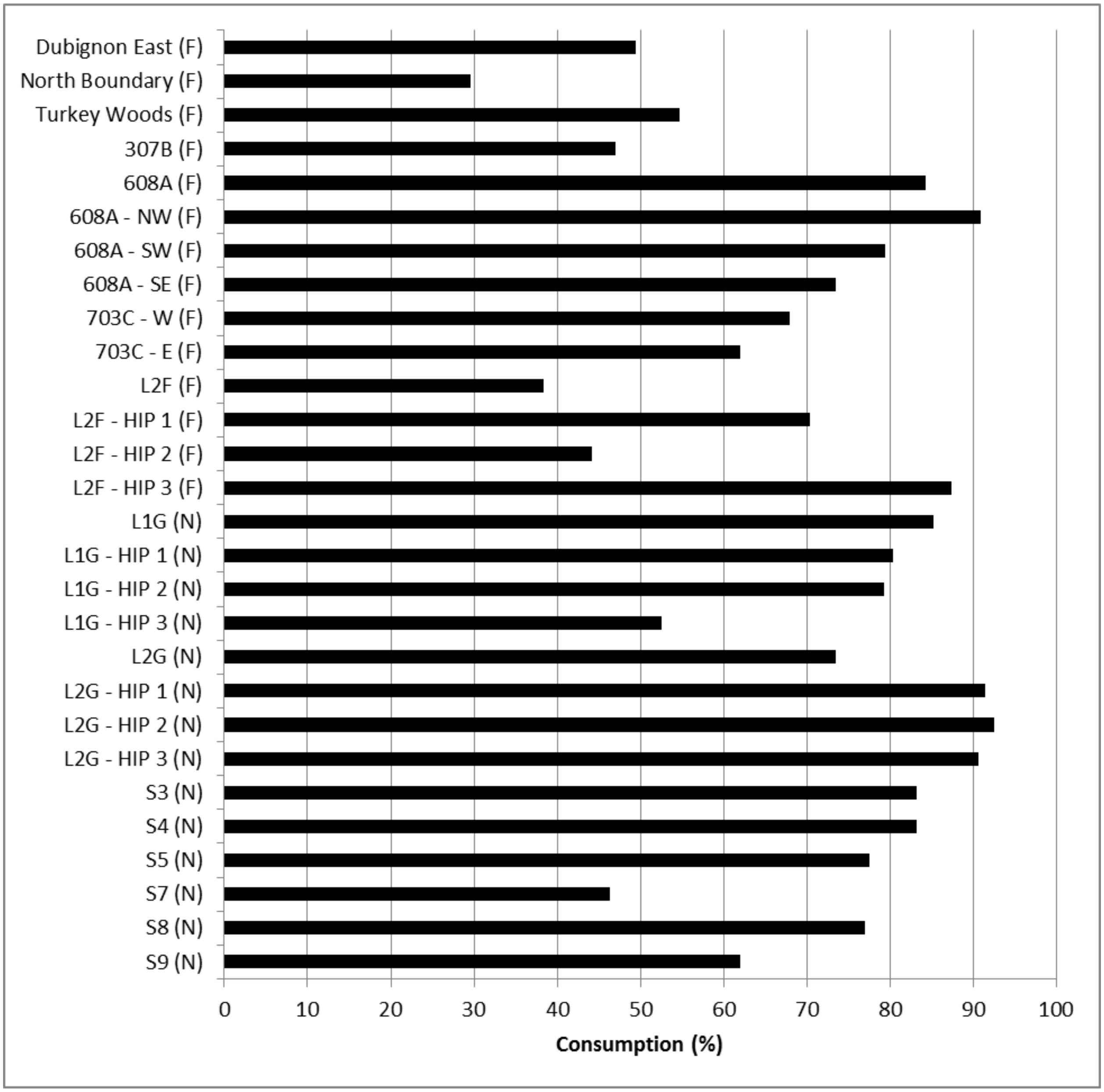

Fig. 7. Relative consumption for all fuels in the forest (F) and nonforest (N) sample sites.

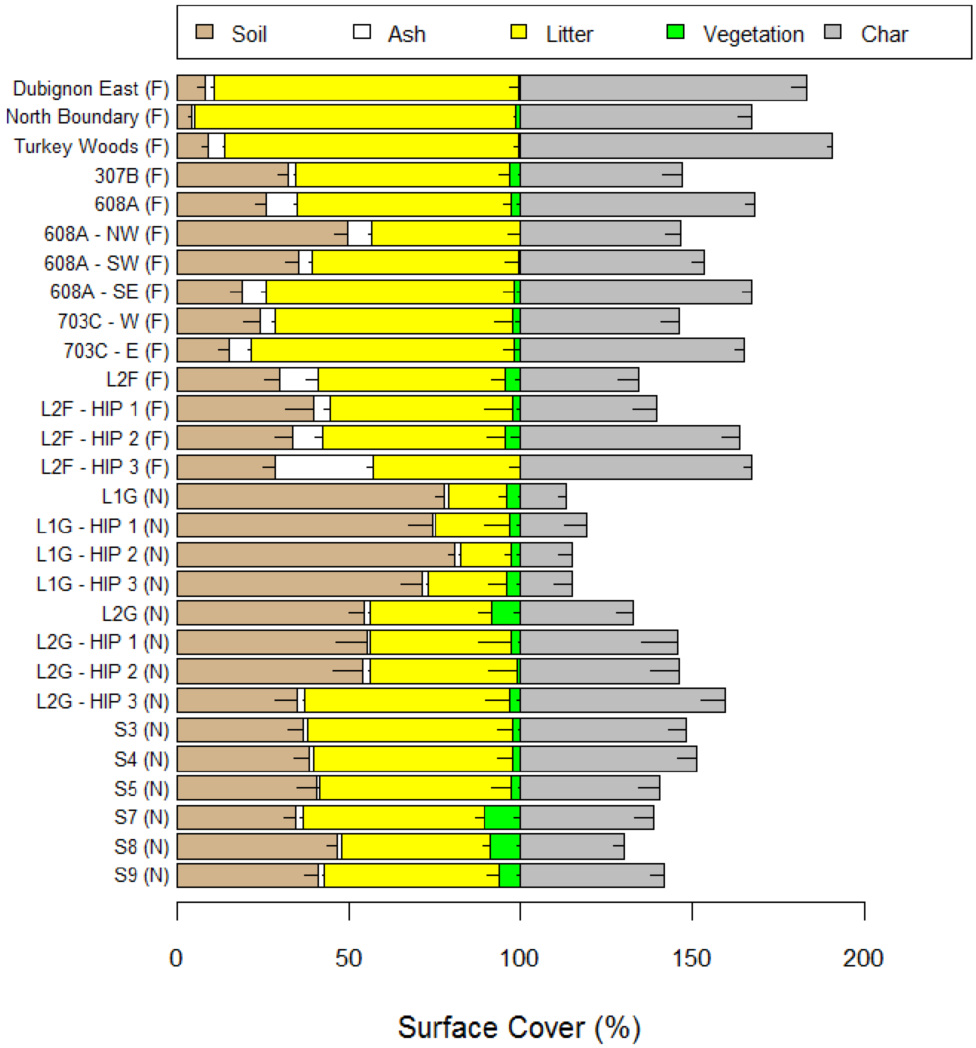

Fig. 8. Mean (SE bars) percentage cover of postfire surface materials ocularly estimated at the postfire clip plots in 28 sample units. The mineral soil, white ash, litter, and green vegetation fractions were constrained to sum to 100%, while the black char fraction is the proportion of the postfire plot that was charred.

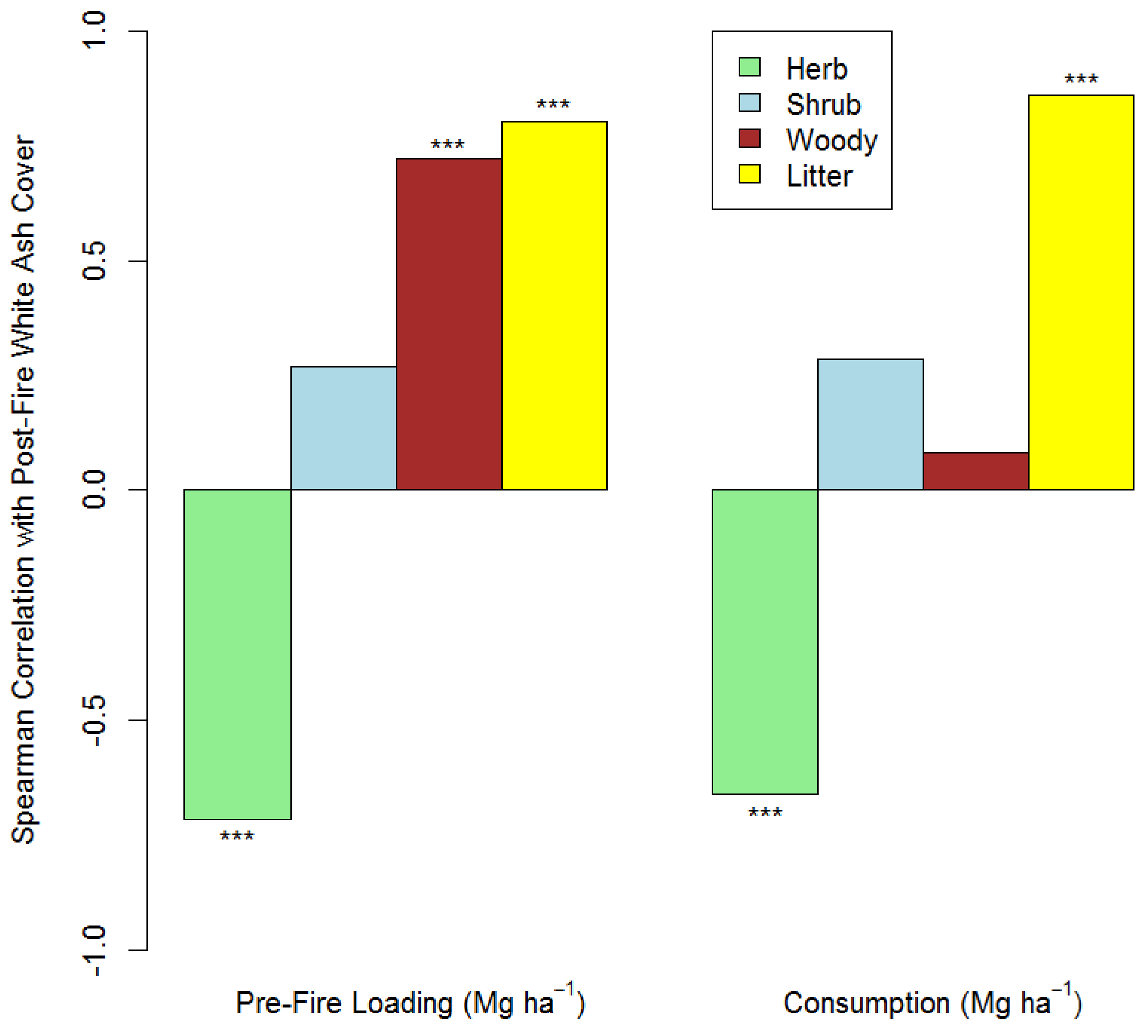

Fig. 9. Spearman (**$\hat{\rho}$**) correlations between postfire white ash fraction (%) and herb, shrub, woody, and litter components of prefire fuel loadings (left) and consumption (right). Significant correlations are indicated as: ***, *P* <0.001.

Table 1. Spearman ($\hat{\rho}$) correlations between surface fuel loading or consumption versus postfire surface cover fractions

Significant correlations are indicated as follows: ***, *P* <0.001; **, *P* <0.01; *, *P* <0.05.

	Green vegetation (%)	Litter (%)	Black char (%)	White ash (%)	Mineral soil (%)
Prefire loading (Mg ha^{-1})	-0.39*	0.64***	0.68***	0.73***	-0.79***
Postfire loading (Mg ha^{-1})	-0.04	0.61***	0.42*	0.53**	-0.77***
Consumption (Mg ha^{-1})	-0.46*	0.42*	0.58**	0.76***	-0.52**
Consumption (%)	-0.27	-0.37	-0.06	-0.15	0.48*