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Predicting forest floor and woody fuel consumption from prescribed burns in southern and western pine ecosystems of the United States

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ABSTRACT

Reliable estimates of pre-burn biomass and fuel consumption are important to estimate wildland fire emissions and assist in prescribed burn planning. We present empirical models for predicting fuel consumption in natural fuels from 60 prescribed fires in ponderosa pine-dominated forests in the western US and 60 prescribed fires in long-needle pine forests in the southeastern US. There was high variability across sites, but total surface fuel biomass was generally much lower on southern sites ($23.0 \pm 11.6\,\mathrm{Mg\,ha^{-1}}$) than western sites ($61.5 \pm 35.8\,\mathrm{Mg\,ha^{-1}}$). Differences in surface fuel composition, pre-burn loading and fuel consumption between the southern and western pine consumption datasets justify the development of regional models for predicting fuel consumption. Southern pine models of herb, shrub and 1-h consumption have close model fit with narrow prediction intervals across the range of sampled values. Relationships between 10-h and 100-h pre-burn loading and consumption produced models with reasonable fit but with no significant correlation with fuel moisture. Model fit of litter and duff consumption models was relatively poor compared to the other southern fuel categories. Western models were developed for 1-h, 10-h and 100-h fine wood, sound coarse wood, rotten coarse wood, litter and duff. All western models had high coefficients of variability, and model residuals indicate higher uncertainty with increasing pre-burn biomass. Although empirical models are widely used, they have limitations in that they are constrained by burning conditions and ranges of predictor variables.

1. Introduction

In many fire-prone ecosystems, fire exclusion over the past century has led to extensive changes in vegetation composition, structure and accumulated surface fuels (Stephens et al., 2012; Mitchell et al., 2014; Hessburg et al., 2016). Fuel reduction treatments including mechanical thinning, piling, mastication, broadcast prescribed burning, and managed fires from natural ignitions (hereafter "managed wildfires") are being used to restore forests and savannas with historically frequent fire regimes to more open stand conditions and to mitigate fire intensity and severity in potential future wildfires (Marshall et al., 2008; Reinhardt et al., 2008; Fulé et al., 2012; Hessburg et al., 2015). Prescribed fire and managed wildfires are particularly effective at reducing subsequent wildfire behavior and effects in low elevation, pine-dominated forests and savannas (Brose and Wade, 2002; Finney et al., 2005; Safford et al., 2009; North et al., 2012; Prichard and Kennedy, 2014; Kennedy and Johnson, 2014; Kreye et al., 2014). Wildland fires are often restricted in their application due to potential air quality degradation and risks that fires may escape containment areas (Quinn-Davidson and Varner, 2012; Ryan et al., 2013; Kobziar et al., 2015).

Consumption of wildland fuels is defined as the mass of live and/or dead vegetation that is combusted during wildland fire (Ottmar, 2014). Factors driving the process of combustion in wildland fuels include the amount, spacing and configuration of fuels, which influence oxygen availability and heat transfer, and environmental variables including temperature, relative humidity, precipitation and wind (Finney and McAllister, 2011). Consumption of fine fuels with high surface area-to-volume ratios is highly dependent on short-term fluctuations in air temperature and relatively humidity which can rapidly change the availability of fuels for burning. Consumption of coarse wood and organic soils tend to be more dependent on fuel moisture (trends in precipitation). Wind influences fuel consumption through its influence on airflow, oxygen availability and fire spread (Finney and McAllister, 2011).

Reliable estimates of pre-burn biomass and fuel consumption are important for mitigating smoke impacts and prescribed burn permitting. Fuel consumption predictions are used to estimate pollutant emissions and model smoke dispersion (Goodrick et al., 2010; Ottmar,

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2014); accurate estimates of pre-burn biomass and fuel consumption are key to reducing uncertainty in smoke modeling (Riebau and Fox, 2001). Modeled estimates of pollutant emissions are more sensitive to the amount of fuel consumed than selection of appropriate emissions factors (Sandberg, 1980; Ottmar et al., 2009; Ottmar, 2014). In particular, underestimating fuels that contribute to long-term smoldering combustion, such as deep forest floor layers, can result in large underpredictions of pollutant emissions (Ottmar, 2014), which can cause unexpectedly high concentrations of smoke in sensitive areas. Alternatively, overestimating potential fuel consumption can limit the area permitted for prescribed burning or managed wildfires.

A number of empirical and semi-empirical consumption models have been developed and incorporated into two software tools for estimating fuel consumption in the United States and parts of Canada including Consume (Ottmar et al., 1993; Prichard et al., 2007) and the First Order Fire Effects Model (FOFEM; Albini and Reinhardt, 1997; Reinhardt et al., 1997). Early studies developed fuel consumption models for a range of forest types throughout the western US but mostly focused on prescribed fires in dispersed logging slash and organic soil matter (i.e., forest litter and duff) in Douglas-fir, western hemlock and hardwood forests of the Pacific Northwest (Sandberg, 1980; Little et al., 1982; Sandberg and Ottmar, 1983; Little et al., 1986; Harrington, 1987; Hall, 1991) and mixed conifer forests of the northern Rocky Mountains (Brown et al., 1991; Hardy, 1996; Reinhardt et al., 1991). In addition, several studies have quantified fuel consumption in forests of the southeastern US, including longleaf, slash and loblolly pine forests with predominantly palmetto-gallberry understories in Florida, Georgia and South Carolina (Hough, 1978; Reid et al., 2012; Wright, 2013), pine and mixed hardwood forests in the upper coastal plain of South Carolina (Scholl and Waldrop, 1999; Sullivan et al., 2003), and shortleaf pine-grass assemblages in Arkansas (Sparks et al., 2002).

In this paper we present empirical models for predicting fuel consumption in natural fuels (i.e., fuel assemblages resulting from natural ecological processes such as growth, senescence and mortality) that were developed by using measurements from 60 prescribed fires in long-needle pine forests in the southeastern coastal plain of northern Florida and southern Georgia (Fig. 1a) and 60 prescribed fires in ponderosa pine-dominated forests in the western US (Fig. 1b). The consumption data from these prescribed fires informed the development of natural fuel consumption models within Consume versions 3.0 and 4.0 (Prichard et al., 2007) and were used in a validation study of Consume and FOFEM in estimating fuel consumption in southeastern pine forests (Prichard et al., 2014). This study presents updated source datasets and fully revised and tested models to be incorporated into the current version of Consume (version 4.3, http://www.fs.fed.us/pnw/fera/fft) and may be also used to refine fuel consumption models in subsequent versions of FOFEM. Previous consumption models in Consume were not peer reviewed nor were they compared with independent datasets.

Within similar vegetation types and burning conditions, predictive models can be used to estimate fuel consumption and emissions from wildland fires. Due to the different climate regimes and understory vegetation characteristics between southern and western pine forests, we anticipated that different equations would be necessary to model consumption in these different regions. Our study compared pre-burn biomass, day of burn fuel moisture and measured consumption between the two regions to determine whether regionally-specific equations were warranted. We also used a comparison dataset of relevant observations, compiled from a literature review of published consumption studies, to assess how broadly representative our study datasets are within similar southern and western pine forests.

2. Methods

2.1. Study areas

Fuel consumption during prescribed fires in southern pine forests were sampled during several field campaigns (Fig. 1a) including 18 sites at Eglin Air Force Base in northwest Florida to support early southern pine consumption models in Consume 3.0 (Ottmar et al., 2006; Prichard et al., 2007), 32 sites across northern Florida and in southern Georgia (Wright, 2013), and 10 additional sites in in northern Florida (Cronan et al., 2015). Dominant overstory trees included longleaf pine (*Pinus palustris* Mill.), slash pine (*P. elliottii* Engelm.), sand pine (*P. clausa* (Chapm. ex Engelm.) Vasey ex Sarg.), loblolly pine (*P. taeda* L.), and pond pine (*P. serotina* Michx.). Understory vegetation included mesic flatwoods and sandhill forest or savanna and typically included saw palmetto (*Serenoa repens* (W. Bartram) Small), gallberry (*Ilex glabra* (L.) A. Gray), turkey oak (*Quercus laevis* Walter) and wiregrass (*Aristida stricta* Michx). All burns were conducted during the dormant season (November through March) and burned within prescription windows specified in each burn plan. Fires were generally ignited as strip head fires by using drip torches.

A total of 60 prescribed fires were sampled in ponderosa pine-dominated forests in Arizona, eastern Oregon, eastern Washington and Montana (Fig. 1b). Sites were selected to span a range of elevations but were confined to slope gradients less than 60 percent and where fuels were relatively homogenous. Dominant trees included ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) with grass and mixed shrub understories. Ignition technique and pattern varied at the discretion of fire personnel and included ground ignition with drip torches and aerial ignition with exothermic spheres. All burns were conducted under prescription windows specified in individual burn plans and were burned in the spring or fall. Sites were generally unmanaged, but nine sites had been thinned prior to burning and contained scattered logging slash (Prichard et al., 2017).

2.2. Pre- and post-burn fuel sampling

Fuel consumption was measured as the difference between sampled pre- and post-burn biomass in the following categories: shrubs, herbs (i.e., graminoids and forbs), downed wood by time lag class (Brown, 1974), litter and duff. Forest litter is defined as undecomposed dead plant matter that has fallen to the ground (i.e., the Oi soil horizon). Duff is defined as partially to fully decomposed litter (i.e., the Oa and Oe soil horizons). Downed wood time lag size classes are defined by diameter thresholds and include 1-h (< 0.64 cm), 10-h (0.64–2.54 cm), 100-h (2.54–7.62 cm), sound large down wood (SLDW, > 7.62 cm) and rotten large downed wood (RLDW, > 7.62 cm). Fires were generally ignited as strip head fires by using drip torches.

Pre- and post-fire biomass were measured in sample plots and transects that were placed systematically along grids within areas with relatively uniform fuels and vegetation. A minimum of nine pre-burn and nine post-burn sampling grid points were established before each prescribed fire. Grid points, spaced 40 m apart, were marked with steel poles and downed wood was measured along transects that originated from each grid point. Abrupt changes in vegetation or site discontinuities (e.g., steep slopes, rocky outcrops, and riparian areas) were avoided during plot setup.

At southern sites, fine surface fuels (i.e., shrubs, herbs, and fine downed wood (FDW, < 7.6 cm in diameter)) were inventoried using destructive sample plots. A minimum of nine pre-burn and nine post-burn clip plots were sampled within each inventory unit. Live and dead vegetation was clipped from within a square plot, bagged and returned to the laboratory, oven-dried at 100 °C for a minimum of 48 h until a constant weight was achieved and then weighed with a precision balance to determine dry-weight biomass (Prichard et al., 2006, Wright, 2013). Shrubs were generally collected within 4-m^2 square plots and included all live and dead shrub biomass that was rooted inside of the plot. Grasses, forbs, litter and duff were sampled within smaller plots (0.5–1-m^2) nested within each shrub biomass plot. SLDW and RLDW were surveyed along 20–30-m long planar intersect transects (Brown,

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