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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,

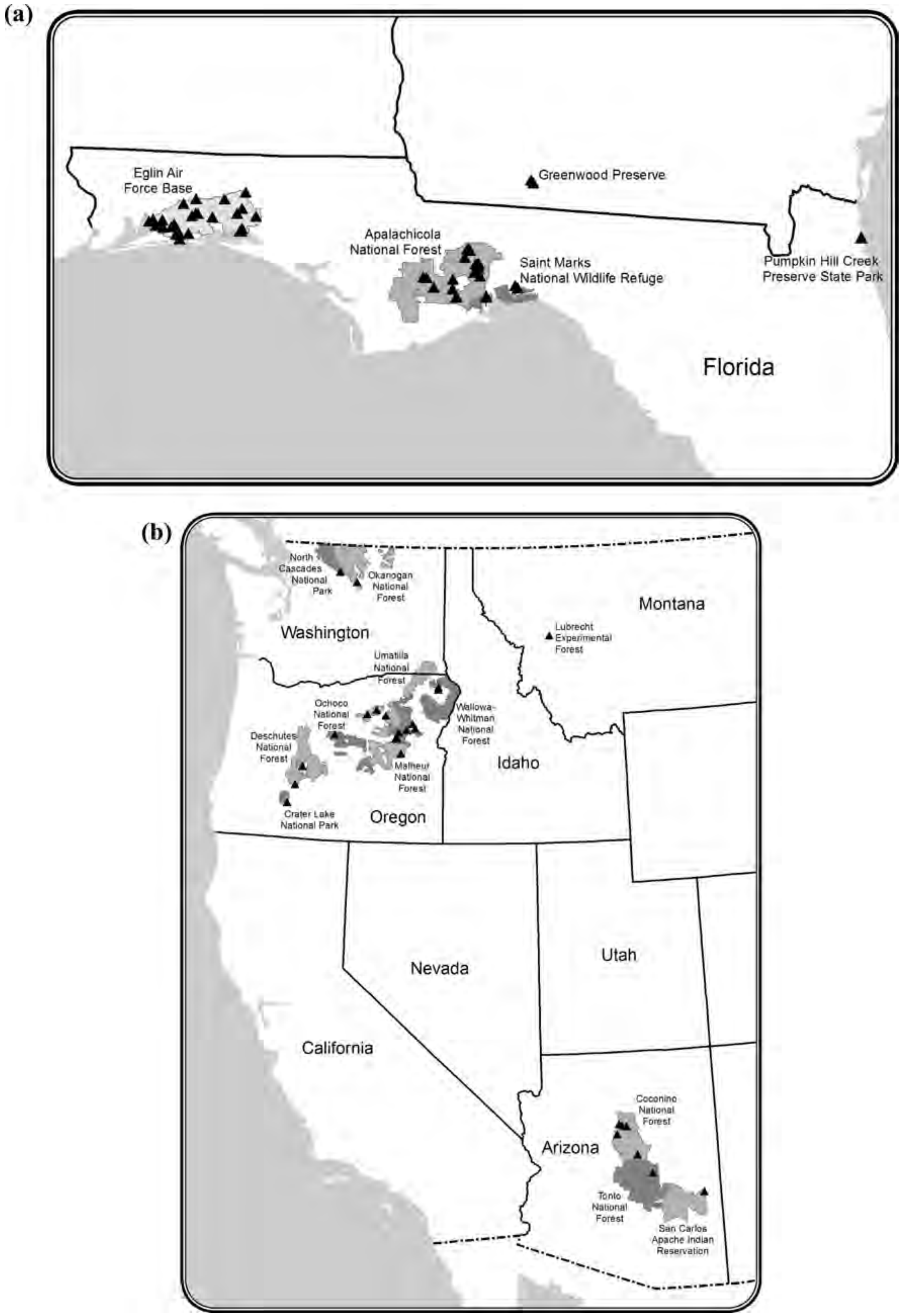

Fig. 1. Southern (a) and western (b) pine site locations.

1974) before and after each prescribed fire. Where large downed wood was abundant, we used an alternate technique for determining large woody fuel consumption. We measured diameter reduction on a randomly selected sample of 20 logs > 7.62 cm in diameter at least three meters in length that were randomly selected from the area covered by the gridded plot design. Prior to burning, a steel wire was wrapped and secured tightly at a perpendicular angle to the mid-point of a log such that the length of the wire became a measurement of pre-burn circumference. Following burning, each wire was pulled tightly around the remaining section of the log; the new length represented the post-burn circumference. Circumference was converted to diameter by dividing by pi, and the difference between measurements was used to calculate absolute and fractional diameter reduction. Fractional diameter reduction was multiplied by pre-burn biomass, which was derived from a planar intersect inventory, to calculate large downed wood consumption.

At western sites, shrubs and grasses were absent or uncommon on most sites and were not sampled. Large downed wood consumption was sampled using the same methods as for southern pine sites. However, fine wood was measured on planar intersect transects (Brown, 1974) before and after each fire instead of the fixed area plot sampling approach used in southern sites. The length of transect that was sampled was dependent on the fine wood size class, with transect length increasing with size class. One and 10-h time lag classes were tallied as a single class across all western sites. Litter and duff consumption were measured as depth reduction using steel nails (hereafter referred to as pins) inserted vertically into the forest floor prior to the burn. Sixteen pins were placed systematically within two meters of the origin of the downed wood sampling transects. Each pin was inserted into the forest floor until embedded in mineral soil with the top of the pin flush with the forest floor surface. Litter depth around each pin was measured prior to the fire, taking care not to disturb or alter the litter. Following each fire, the length of the exposed pin and depth to mineral soil were measured. Litter depth reduction was calculated by subtracting the length of the exposed pin (up to the depth of the pre-burn litter) from the pre-burn litter depth. Pre-burn duff depth was calculated by subtracting pre-burn litter depth from the depth to the mineral soil, and duff reduction was calculated by subtracting the pre-burn litter depth from the length of the exposed pin. Pre-burn depths and post-burn reduction were multiplied by material-specific bulk density values to calculate litter and duff biomass and mass consumed.

Day-of-burn fuel moisture samples were collected prior to ignition at all sites. Samples of 10-h and 100-h downed wood, litter and duff were collected across the entire area within the burn unit covered by gridded plots and stored in heavy-gauge, air-tight plastic bags. Live fuels (e.g., grasses, forbs and shrubs) were also collected by lifeform to assess moisture content. Samples were weighed within eight hours of being collected, oven-dried at 100 °C for a minimum of 48 h until a constant weight was achieved and then reweighed with a precision balance determine gravimetric moisture content. For 1000-h downed wood, each wired log ($\geq$7.62 cm) was sampled for fuel moisture by sawing disks from near the small and large ends; samples were dried and weighed, as above. Individual log final fuel moisture was recorded as the average of the two disks.

2.3. Statistical analysis and model selection

Pre-burn fuel loading (Mg ha^{-1}), fuel consumption (Mg ha^{-1}), and gravimetric fuel moisture content (%) were summarized by fuel category (shrub, herb, downed wood by time lag class, litter and duff) for each inventory unit. Table 1 summarizes fuel loading, consumption and sample size by fuel category; not all fuel categories were present on every site. Simple and multiple ordinary least squares (OLS) regression models were constructed in R (R Core Team 2016). Pre-burn fuel loads and fuel moisture specific to each fuel category (e.g., pre-burn 10-h load and fuel moisture) were tested as predictor variables in addition to pre-burn fuel loading and fuel moistures of other fuel categories. Final models were selected based on lowest Aikake's Information Criterion (AIC) values and generally included pre-burn loading and fuel moisture as predictor variables. Because most models exhibited a mean-variance relationship in the residuals, we constructed final models and prediction intervals using weighted least squares regression (R Core Team 2016) with weights defined as 1/pre-burn load. Prediction intervals were calculated across the sampled range of pre-burn loading. For models that had a second predictor variable such as 1000-h, litter or duff fuel moisture, the average of sampled values was used for prediction interval estimation.

Several environmental variables including mid-flame wind speed, days since rain, relative humidity, and temperature were collected at the southern pine sites that were not sampled at the western pine sites. None of these variables were included in final models, however, either due to lack of significance or lack of reduction in model AIC values. Fuel moisture of downed wood by time lag class (10-h, 100-h, and 1000-h), litter and duff was collected in both study locations and was a significant predictor variable in litter and duff consumption models for both regions, and in large wood consumption models in the western region.

Significant models were selected for herb, shrub, 1-, 10- and 100-h downed wood, litter and duff consumption in the southern region. Herb and shrubs were not sampled at the western pine sites, and 1-h and 10-h downed wood was collected together. For the western region, final models were selected for combined 1- and 10-h (hereafter referred to as 10-h), 100-h, SLDW, RLDW, litter and duff consumption.

We compared the distribution of our model source data with published fuel consumption studies (Prichard et al., 2017). Fuel moisture values were lacking for many published studies, so we were only able to compare published distributions of pre-burn biomass and fuel consumption with our study datasets. Published consumption studies for southern pine sites included Clinton et al. (1998), Scholl and Waldrop (1999), Sullivan et al. (2003), Kolaks (2004) and Reid et al. (2012). Western comparison data were compiled from the following studies: Sacket (1980), Little et al. (1982), Brown et al. (1985), Ottmar et al. (1985), Ottmar (1987), Reinhardt et al. (1997), Hille and Stephens (2005), Knapp et al. (2005) and Agee and Lolley (2006).

3. Results

There was high variability across sites, but total surface fuel biomass was generally was much lower on southern sites (23.0 ± 11.6 Mg ha^{-1}) than western sites (61.5 ± 35.8 Mg ha^{-1}) (Table 1). Southern surface fuel biomass was comprised mostly of fine fuels including litter and shrubs (Fig. 2). Heavier accumulations of large downed wood and duff on western sites contributed to higher fuel biomass and greater fuel consumption than southern sites. Despite overall differences in pre-burn surface and ground fuel biomass, roughly half of pre-burn biomass was consumed in both study regions with slightly higher proportional consumption in southern sites than in western sites (Table 1).

3.1. Southern pine sites

Simple linear consumption models were selected for herbaceous and shrub and models, relating fuel consumption to pre-burn biomass (Table 2). The herb consumption model had a close fit to source data with low uncertainty across the range of pre-burn loads. A total of 22 observations were available in the comparison dataset of published values; all were at the low range of pre-burn biomass and consumption. Although the shrub model had a high coefficient of determination (R^2 = 0.94), 95% prediction intervals widened at higher pre-burn biomass and consumption values (Fig. 3, Table 3). For example, at the highest sampled pre-burn shrub biomass (14.4 Mg ha^{-1}), predicted consumption was 10.1 Mg ha^{-1} with 95% prediction interval of 6.9–13.4 Mg ha^{-1}. A total of 8 observations were available in the comparison dataset and were at the low range of pre-burn biomass and consumption.

Simple linear models were also selected for all fine wood classes. The 1-h model had a high coefficient of determination (R^2 = 0.97) and narrow prediction intervals, with only a slight increase in prediction

Table 1
Pre-burn biomass and consumption by fuel category for southern pine and western pine sites. Fuel categories include: herbaceous (herb), shrub, fine wood by timelag class (1-h, 10-h, and 100-h), coarse wood in sound, rotten and total categories (SLWD, RLWD, TLWD), litter and duff.

		Pre-burn biomass (Mg ha^{-1})		Consumption (Mg ha^{-1})		Consumption (%)		Fuel moisture (%)		
		Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range		Mean ± SD	Range
	n	Mg ha^{-1}				%		n	%	
Southern sites										
Total	60	23.0 ± 11.6	5.3–64.1	12.7 ± 7.2	1.3–33.7	57.4 ± 22.3	10.4–93.5	–	–	–
Herb	42	0.8 ± 1.3	0–8.3	1.0 ± 1.4	0–8.1	90.2 ± 24.0	0–100	–	–	–
Shrub	42	3.8 ± 3.6	0–14.4	3.6 ± 2.5	0.3–11.6	69.4 ± 18.9	14.4–98.1	–	–	–
1 h	44	0.7 ± 1.1	0–5.7	0.8 ± 1.0	0–4.6	77.4 ± 25.2	0–100	–	–	–
10 h	60	1.7 ± 1.4	0.3–5.7	0.6 ± 0.7	0–3.5	34.1 ± 28.3	0–100	58	40.9 ± 21.5	8.8–83.5
100 h	60	1.3 ± 1.9	0–10.3	1.1 ± 1.4	0–6.3	47.1 ± 38.7	0–100	18	44.5 ± 20.3	12.8–80.9
SLWD	37	1.0 ± 2.2	0–13.0	0.1 ± 0.1	0–0.8	10.5 ± 25.6	0–100	–	–	–
RLWD	36	0.8 ± 1.2	0–5.2	0.0 ± 0.1	0–0.5	16.3 ± 39.4	0–100	–	–	–
TLWD	39	3.7 ± 6.2	0–30.8	0.3 ± 0.5	0–2.0	9.2 ± 18.3	0–95.4	22	91.6 ± 39.4	18.2–210.1
Litter	60	8.9 ± 6.8	1.8–29.6	6.9 ± 5.9	0.7–26.2	74.7 ± 25.4	11–100	42	23.5 ± 11.6	7.0–48.8
Duff	18	4.0 ± 6.8	2.5–23.2	1.3 ± 1.4	0.1–4.5	9.8 ± 8.7	1.1–26.0	18	47.4 ± 34.8	5.6–111.3
Western sites										
Total	60	61.5 ± 35.8	11.7–176.8	29.7 ± 24.5	2.5–113.7	45.2 ± 18.8	9.0–85.3	–	–	–
1 & 10 h	60	3.2 ± 2.7	0.1–13.2	2.7 ± 2.5	0.1–12.3	83.3 ± 15.1	34.7–100	59	18.6 ± 10.8	7.0–85.0
100 h	59	4.2 ± 2.7	1.1–14.1	3.0 ± 2.5	0–13.5	69.3 ± 24.5	0–100	60	24.2 ± 8.2	8.0–44.0
SLWD	60	15.2 ± 17.9	1.52–92.0	5.2 ± 7.5	0.2–40.6	36.2 ± 25.1	1.3–95.2	–	–	–
RLWD	60	10.9 ± 9.7	0.22–50.1	5.4 ± 5.9	0–26.7	50.5 ± 32.8	0–100	–	–	–
TLWD	60	26.1 ± 24.4	3.8–126.3	10.5 ± 11.5	0.2–55.2	42.3 ± 27.0	1.7–94.6	60	56.3 ± 18.3	19.0–111.0
Litter	60	5.1 ± 2.5	0.2–11.0	3.1 ± 2.0	0–8.7	59.1 ± 19.9	0–91	53	18.6 ± 17.8	6.1–124.7
Duff	49	26.6 ± 17.0	2.2–104.2	12.1 ± 16.5	0.2–91.4	36.8 ± 23.6	3.8–89.3	55	52.8 ± 32.0	13.0–154.0

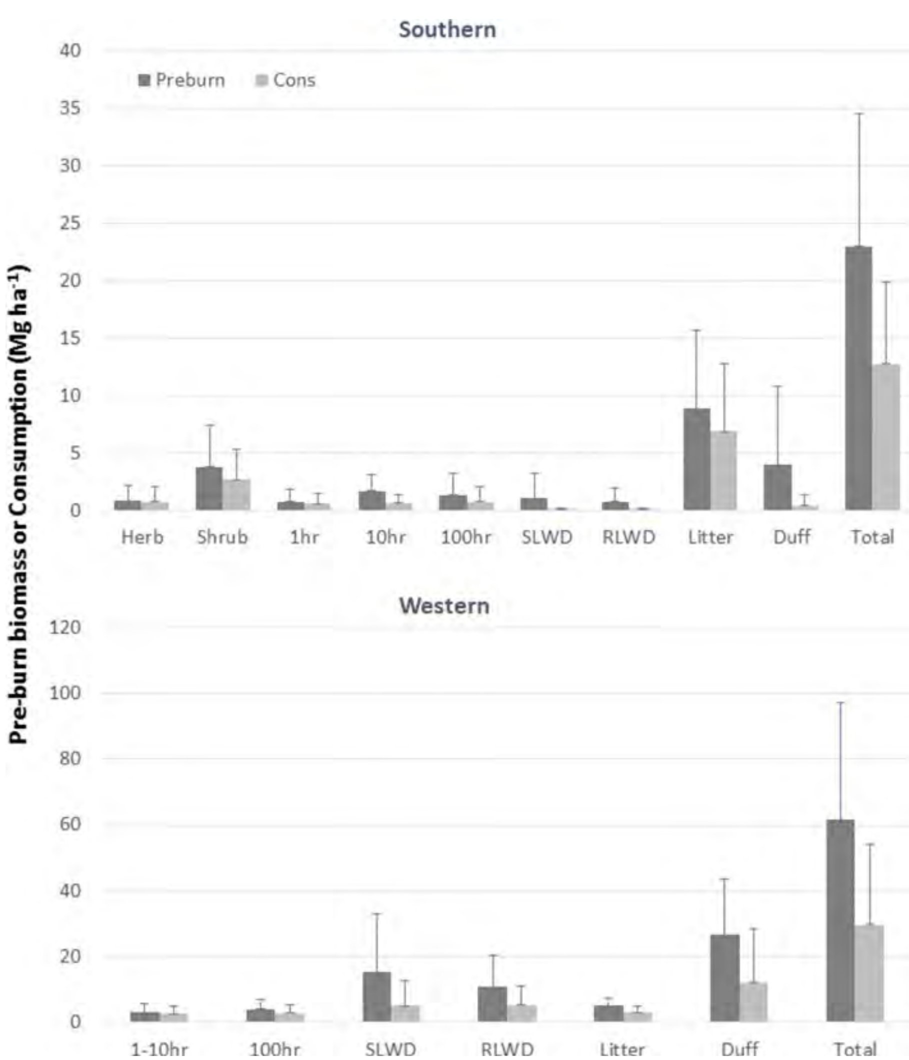

Fig. 2. Comparison of pre-burn and consumed biomass (Mg ha^{-1}) by fuel category. Error bars represent one standard deviation. Western sites lacked live fuel categories, and 1- and 10-h fuels were collected as a single category.

Table 2
Weighted least square regression models for southern and western pine sites, including sample size, model p-values, and coefficients of determination (R^2). Fuel categories include: herbaceous (herb), shrub, fine wood by timelag class (1-h, 10-h, and 100-h), coarse wood in sound, rotten and total categories (SLWD, RLWD, TLWD), litter and duff. Reported models were selected based on lowest AIC for each fuel category.

	Model	n	p-value	R^2	Preload Mg ha^{-1}	Consumption Mg ha^{-1}	Fuel moisture %
Southern							
Herb	y = −0.007 + 0.9626 PreHerb	45	< 0.0001	0.990	0–8.3	0–8.1	–
Shrub	y = −0.0349 + 0.7043 PreShrub	45	< 0.0001	0.944	0–14.4	0.3–11.6	–
1hr	y = −0.0021 + 0.8092 Pre1-h	55	< 0.0001	0.969	0–5.7	0–4.6	–
10hr	y = −0.0725 + 0.4193 Pre10-h	60	< 0.0001	0.592	0.3–5.7	0–3.5	8.8–83.5
100hr	y = −0.1504 + 0.633 Pre100-h	40	< 0.0001	0.770	0–10.3	0–6.3	12.8–80.9
SLWD	y = 0.0585 + 0.0364 PreSLWD	35	0.1047	0.048	0–13.0	0–0.8	18.2–210.1
RLWD	y = 0.0602 + 0.0033 PreRLWD	40	0.8314	0.001	0.1–5.2	0–0.5	–
TLWD	y = 0.4253 + 0.0046 PreTLWD − 0.0023 FM1000	21	0.3143	0.021	0–30.8	0 – 2.0	18.2–210.1
Litter	y = −0.2995 + 0.8166 PreLitter	57	< 0.0001	0.911	1.8–29.6	0.7–26.2	7.0–48.8
Duff	y = 2.9711 + 0.0702 PreDuff − 0.1715 LitterFM	18	0.0023	0.495	0–23.2	0.1–4.5	5.6–111.3
Western							
1 & 10 h	y = −0.0288 + 0.8558 Pre1 & 10	59	< 0.0001	0.966	0.1–13.2	0.1–12.3	7.0–85.0
100 h	y = −0.2210 + 0.7657 Pre100-h	60	< 0.0001	0.763	1.1–14.1	0–13.5	8.0–44.0
SLWD	y = 2.7350 + 0.3285 PreSLWD − 0.0457 FM1000-h	60	< 0.0001	0.523	1.5–92.0	0.2–40.6	19.0–111.0
RLWD	y = 1.9024 + 0.4933 PreRLWD − 0.0338 FM1000-h	60	< 0.0001	0.758	0.2–50.1	0–26.7	–
TLWD	y = 6.3744 + 0.3923 PreTLWD − 0.108 FM1000-h	60	< 0.0001	0.593	0.2–11.0	0–8.7	6.1–124.7
Litter	y = 0.3509 + 0.6610 PreLitter − 0.0120 DuffFM	49	< 0.0001	0.885	2.2–104.2	0.2–91.4	13.0–154.0
Duff	y = −2.0510 + 0.6855 PreDuff − 0.0779 DuffFM	54	< 0.0001	0.812	0.1–13.2	0.1–12.3	7.0–85.0

intervals at higher pre-burn loading values (Fig. 3). Available comparison data (n = 18) closely corresponded with our sample distributions but with a bias toward 100% consumption. Day-of-burn 10-h fuel moisture averaged 41 ± 22% with a broad sample range between 9 and 84%. However, 10-h fuel moisture was not a significant predictor of 10-h consumption. The 10-h model had a relatively low coefficient of determination (R^2 = 0.59) and a wide scatter in model residuals, particularly at higher pre-burn biomass and consumption values. Comparison data (n = 23) were weakly related to pre-burn 10-h biomass and consumption (Fig. 3); comparison sites with 2–4 Mg ha^{-1} of pre-burn 10-h fuels displayed a wide range in measured consumption. The 100-h model had a reasonable fit (R^2 = 0.77), but many sampled points fell either below or above prediction intervals, and intervals widened at high biomass values. For example, near the low end of our sampled pre-burn 100-h fuel loading (2.38 Mg ha^{-1}), 95% prediction intervals ranged between 0.3 and 2.5 Mg ha^{-1} versus a predicted value of 1.4 Mg ha^{-1} (Table 3). At the high end of pre-burn 100-h fuel loading (10.3 Mg ha^{-1}), predicted consumption was 6.4 Mg ha^{-1} with an estimated range between 3.4 and 9.4 Mg ha^{-1}. Comparison data (n = 11) had low 100-h pre-burn biomass, but plotted pre-burn and consumption distributions were similar to our dataset (Fig. 3).

Large downed wood (> 7.6 cm diameter) was generally sparse and

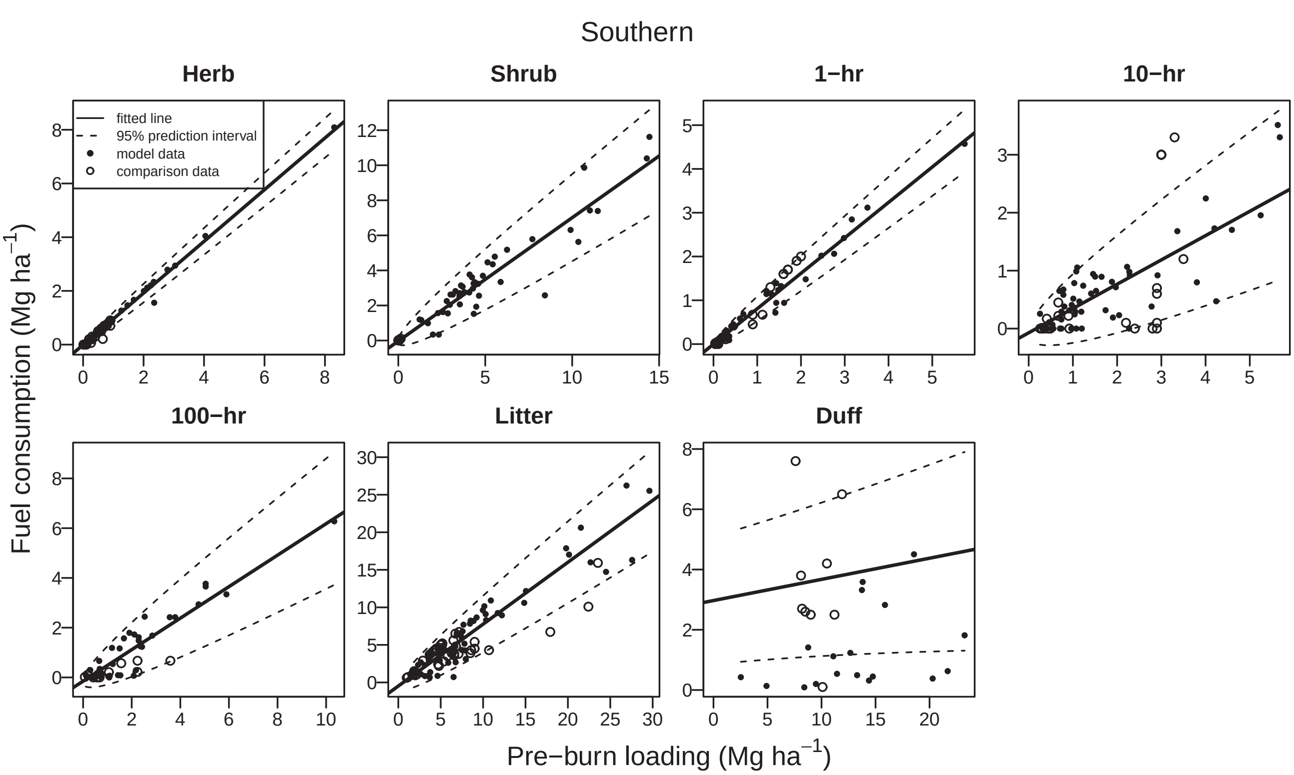

Fig. 3. Scatter plot comparisons of pre-burn biomass and consumption for modeled data and comparison data of southern sites. Mean fuel moisture values were used for multiple regression models. Lines represent model values (solid line) and 95% prediction intervals (dashed lines) for weighted least squares regressions.

Table 3
Southern fuel consumption model predictions, including low and high prediction intervals across 10% increments of sampled pre-burn biomass for herbs, shrubs, 1-h wood, 10-h wood, 100-h wood, and litter.

Herb	Predicted	Low	High	Shrub	Predicted	Low	High
0.01	0.0	−0.1	0.1	0.1	0	−0.8	0.8
0.93	0.9	0.7	1.1	1.7	1.1	0.0	2.2
1.85	1.8	1.5	2.1	3.3	2.3	0.9	3.6
2.78	2.7	2.3	3.0	4.9	3.4	1.8	5.0
3.7	3.6	3.1	4.0	6.5	4.5	2.6	6.4
4.62	4.4	3.9	5.0	8.1	5.6	3.5	7.8
5.54	5.3	4.7	6.0	9.6	6.8	4.3	9.2
6.47	6.2	5.5	6.9	11.2	7.9	5.2	10.6
7.39	7.1	6.3	7.9	12.8	9.0	6.1	12.0
8.31	8.0	7.1	8.9	14.4	10.1	6.9	13.4
1-h wood	Predicted	Low	High	10-h Wood	Predicted	Low	High
0.0	0.0	−0.1	0.1	0.3	0.0	−0.4	0.5
0.7	0.5	0.3	0.7	0.9	0.3	−0.3	0.8
1.3	1.0	0.8	1.3	1.5	0.5	−0.1	1.2
1.9	1.6	1.2	1.9	2.1	0.8	−0.0	1.6
2.6	2.1	1.6	2.5	2.7	1.1	0.1	2.0
3.2	2.6	2.1	3.1	3.3	1.3	0.2	2.4
3.8	3.1	2.5	3.7	3.9	1.6	0.4	2.7
4.5	3.6	2.9	4.3	4.5	1.8	0.5	3.1
5.1	4.1	3.4	4.9	5.1	2.1	0.6	3.5
5.7	4.6	3.8	5.5	5.7	2.3	0.7	3.9
100-h Wood	Predicted	Low	High	Litter	Predicted	Low	High
0.1	−0.1	−0.6	0.5	1.9	1.7	−0.6	3.7
1.3	0.6	−0.2	1.5	3.0	2.4	−0.2	4.7
2.4	1.4	0.3	2.5	4.2	3.1	0.2	5.8
3.5	2.1	0.7	3.5	5.3	3.8	0.6	6.8
4.7	2.8	1.2	4.4	6.5	4.4	1.1	7.9
5.8	3.5	1.6	5.4	7.6	5.1	1.5	8.9
6.9	4.2	2.0	6.4	8.8	5.8	1.9	10.0
8.1	5.0	2.5	7.4	9.9	6.5	2.3	11.0
9.2	5.7	2.9	8.4	11.1	7.2	2.7	12.1
10.3	6.4	3.4	9.4	12.2	7.8	3.1	13.1

unevenly distributed on southern sites with a total mean pre-burn biomass of 3.7 ± 6.2 Mg ha^{-1}. Only 36 of 60 sites contained large wood. No significant models of consumption were found for sound, rotten or total large wood consumption (Table 2).

Pre-burn litter biomass and 1000-h fuel moisture were significant predictor variables in one litter consumption model (R^2 = 0.72), but because 1000-h fuels were rare or absent on many sites, the final model was based on pre-burn loading (R^2 = 0.91). Comparison data (n = 44) were confined to lower pre-burn biomass values (≤5.2 Mg ha^{-1}) but with similar distributions to our dataset.

Duff was present and measured on only 18 of the 60 sites and where present, had a low percent consumption (mean 9.8 ± 8.7%). The final model of duff consumption included pre-burn duff biomass and litter fuel moisture as significant predictor variables and had a relatively low coefficient of determination (R^2 = 0.49). Comparison data (n = 12) have a wide range in consumption values from no consumption to complete consumption (Fig. 3).

3.2. Western pine sites

Fuel moisture was not a significant predictor of consumption in either the 1 & 10-h or the 100-h consumption models, and simple linear models were selected for fine wood classes on western sites. The 1 & 10-h model had a close fit with observed values (R^2 = 0.97); prediction intervals were narrow and only widened slightly at higher biomass values (Fig. 4). Comparison data (n = 10) generally had higher consumption for a given pre-burn loading than our observations. The 100-h model also had a high coefficient of determination (R^2 = 0.92) but prediction intervals widened at higher pre-burn biomass (Fig. 4, Table 4). Comparison data (n = 10) spanned a greater range in pre-burn biomass than our sampled values but had a similar relationship between pre-burn biomass and consumption (Fig. 4).

Pre-burn biomass of large downed wood, which was present on all western sites, was highly variable; total LWD had a mean of 26.1 ± 24.4 Mg ha^{-1} and a range of 3.8–126.3 Mg ha^{-1}. Measured 1000-h fuel moisture had a mean of 56 ± 18% and was a significant predictor in models of sound and rotten wood consumption. Model fit of SLDW consumption was relatively low (R^2 = 0.52) with wide scatter at high pre-burn biomass values. Comparison data (n = 6) were confined to lower biomass values but were within the distribution of our dataset. The RLWD consumption model had a higher coefficient of determination (R^2 = 0.76) but also had wide prediction intervals, particularly at upper pre-burn biomass and consumption values. Only 6 observations of rotten wood consumption were available for comparison, and these fit within the distribution of our sample dataset. A total of 58 observations were available for comparison of total large wood (TLWD) and closely corresponded to the sampled distributions within our western dataset.

Pre-burn litter biomass and duff fuel moisture were significant predictor variables in the final model (R^2 = 0.89). Model uncertainty was uneven with a wider upper prediction interval than lower prediction interval (Fig. 4). Six observations were available for comparison and were at or higher than the maximum pre-burn litter biomass in our dataset.

Pre-burn duff biomass and duff fuel moisture were significant predictor variables in the final model of duff consumption (R^2 = 0.81). Model uncertainty was particularly skewed in this fuel category with increasingly wide prediction intervals at higher pre-burn loading values. Duff comparison data (n = 62) were closely aligned with our dataset at low pre-burn loading values (< 50 Mg ha^{-1}) but tended to have much lower consumption at higher pre-burn loading values.

4. Discussion

Differences in surface fuel composition, pre-burn biomass and fuel consumption between the southern and western pine consumption datasets are clearly evident and justify the development of regional models for predicting fuel consumption. Southern sites are dominated by fine fuels including herbaceous vegetation, shrubs and litter, which comprise the majority of total site loading and consumption (Fig. 2). In contrast, western sites have high loading of large downed wood and duff, which make up a substantial fraction of the overall consumption. As expected, owing to the more humid climate, fuel moisture was generally much higher at sites in the southern than the western sites. Despite the generally lower fuel moistures, however, a lower average percent consumption was observed in the western region due to their greater accumulations of coarse wood and duff, which are slower to consume than the fine fuels dominant on southern sites.

With the exception of western litter, source data for the southern and western pine consumption models generally exceeded the range of comparison data (Figs. 3 and 4). This suggests that our models represent a broad range of observed preburn fuel loads and consumption and are likely applicable to similar pine sites and burn prescriptions. However, model uncertainty, represented by wide prediction intervals for cases with high pre-burn biomass, warrants some caution in model application.

4.1. Southern pine models

Models of herb, shrub and 1-h consumption have close model fit with narrow prediction intervals across the range of sampled values. On average, 90% of herbaceous, and 70% of shrub fuels were consumed. Herbaceous consumption was comparable with a recent study of prescribed fires in pine forests of northern Florida, which reported an average of 82 percent consumption (Reid et al., 2012). Prediction

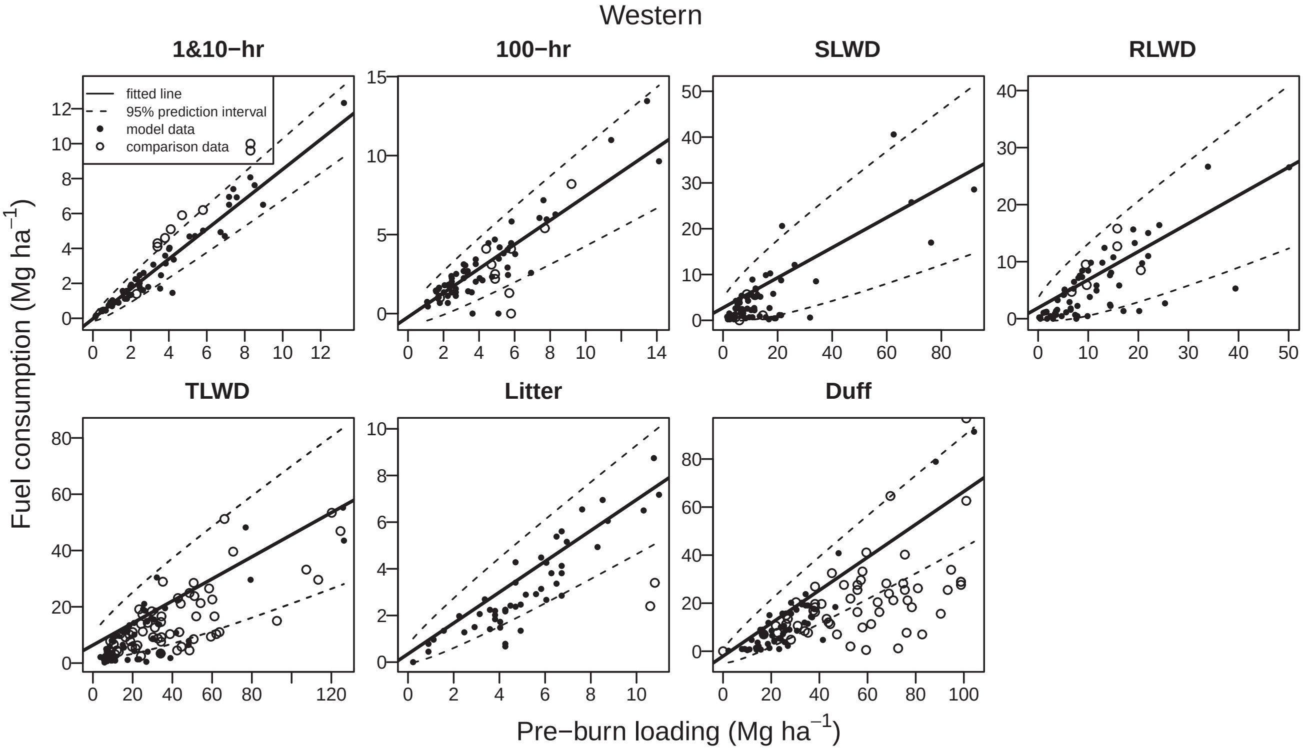

Fig. 4. Scatter plot comparisons of pre-burn biomass and consumption for modeled data and comparison data of western sites. Mean fuel moisture values were used for multiple regression models. Lines represent model values (solid line) and 95% prediction intervals (dashed lines) for weighted least squares regressions.

intervals widen with increasing pre-burn biomass in the southern shrub model and suggest that model error should be reported when applying the model in sites with high shrub biomass. At the upper limits of our sample range (14 Mg ha^{-1}), model uncertainty is 30% of predicted consumption.

Relationships between 10- and 100-h pre-burn loading and consumption produced models with reasonable fit but wider prediction intervals compared to herbaceous, shrub and 1-h models. Because live and dead fuel moisture are variables in fire behavior models (Rothermel, 1972, Jolly, 2007), the lack of correspondence with fuel moisture was unexpected. We evaluated models that related 10- and 100-h consumption with other fine fuel categories including herbaceous, litter and 1-h pre-burn loading but did not find significant relationships. Sampled 10-h fuel moistures ranged from 9 to 84% and are evenly distributed. Our model therefore likely demonstrates a lack of correspondence between 10-h fuel moisture and consumption and is not a sampling artifact.

Although litter consumption was significantly correlated with litter fuel moisture, prediction intervals are particularly wide, and model fit is relatively poor compared to the other southern fuel categories. Percent consumption of litter averaged 74% and ranged between 11 and 100% across sites, suggesting that prescribed burn coverage was not always continuous across units. In comparison, a recent study by Reid et al. (2012) in northern Florida and southern Georgia reported a mean percent fuel consumption of 52% for 217 prescribed fires in longleaf pine-wiregrass and loblolly pine – shortleaf pine forests. Complete litter consumption is generally a prescription goal for prescribed fires in the southern region and is assumed to completely consume by FOFEM (Albini and Reinhardt, 1997). Our model results indicate that this objective may not always be achieved and that for planning purposes, much lower litter consumption might be anticipated and could reduce the predicted consumption and emissions for prescribed burning on southern pine sites.

Where organic soils exist in southern pine forests, estimating duff consumption is a especially critical factor in smoke management planning and predicting other fire effects such as tree mortality following fire in long-unburned sites (Varner et al., 2009, Hood, 2010). Our study focused on areas with active prescribed burn programs – duff was present in only 18 of our 60 study sites, and our model of duff consumption has a poor fit and wide prediction intervals. The 12 comparison data observations also revealed no clear relationship between pre-burn biomass and consumption. The duff consumption model used for southern pine sites within FOFEM is from Hough (1978) and was developed to estimate consumption of the combined litter and duff layers. The lack of available data on duff consumption highlights the need for future consumption studies in southern pine-dominated forests in which fire exclusion has led to the development of organic soil layers. In a multi-scaled study of duff characteristics, Kreye et al. (2014) demonstrated that duff depth, bulk density and moisture content vary substantially at fine spatial scales and concluded that coarse scale (i.e., forest or unit-level) measurements of duff characteristics may be of insufficient resolution to use in duff consumption modeling. Given the importance of deep organic soils to smoke production in fire-excluded sites, this is a challenging reality for smoke management. Varner et al. (2007, 2009) suggest burning during prescription windows in which upper duff layers (termed fermentation layers) are moist from recent significant rainfall events and result in lower duff consumption. This strategy may be an optimal approach not only for mitigating tree mortality impacts but also for reducing smoke impacts while reintroducing fire to long-unburned southern pine ecosystems.

4.2. *Western pine models*

Because herbaceous and shrub fuels were lacking in our western data set, we were unable to develop consumption models for those categories. The 10-h model has reasonable model fit with narrow prediction intervals across the range in sampled values. The 100-h consumption model was affected by relatively uneven distribution in sample data points with most observations falling below 10 Mg ha^{-1} pre-burn biomass and a few outliers at higher pre-burn biomass. Given

Table 4
Western fuel consumption model predictions, including low and high prediction intervals across 10% increments of sampled pre-burn biomass for 1-h, 10-h, 100-h, sound 1000-h, and rotten 1000-h wood, litter and duff.

1 & 10-h wood	Predicted	Low	High	100-h wood	Predicted	Low	High
0.1	0.1	−0.4	0.5	1.1	0.6	−0.6	1.9
1.6	1.3	0.7	2.0	2.5	1.7	0.2	3.3
3.0	2.6	1.7	3.5	4.0	2.8	1.0	4.7
4.5	3.8	2.7	4.9	5.4	3.9	1.7	6.1
6.0	5.1	3.8	6.4	6.9	5.0	2.5	7.6
7.4	6.3	4.8	7.8	8.3	6.2	3.3	9.0
8.9	7.6	5.9	9.3	9.8	7.3	4.1	10.4
10.3	8.8	6.9	10.7	11.2	8.4	4.9	11.8
11.8	10.1	7.9	12.2	12.7	9.5	5.7	13.3
13.2	11.3	9.0	13.6	14.1	10.6	6.5	14.7
SLWD wood	Predicted	Low	High	RLWD wood	Predicted	Low	High
1.5	0.7	−3.2	4.5	0.2	0.1	−2.8	3.2
11.6	4.0	−1.7	9.6	5.8	2.8	−1.6	7.4
21.6	7.3	−0.2	14.7	11.3	5.6	−0.4	11.5
31.7	10.6	1.4	19.8	16.9	8.3	0.8	15.7
41.7	13.9	2.9	24.9	22.4	11.0	2.0	19.9
51.8	17.2	4.4	30.1	27.9	13.8	3.1	24.0
61.8	20.5	5.9	35.2	33.5	16.5	4.3	28.2
71.9	23.8	7.4	40.3	39.0	19.2	5.5	32.4
82.0	27.1	8.9	45.4	44.6	22.0	6.7	36.6
92.0	30.4	10.5	50.5	50.1	24.7	7.8	40.7
Litter	Predicted	Low	High	Duff	Predicted	Low	High
0.2	−0.1	−0.6	0.9	2.2	−4.6	−10.9	1.7
1.4	0.7	−0.0	1.9	13.6	3.2	−5.2	11.6
2.6	1.5	0.5	2.8	24.9	11.0	0.4	21.5
3.8	2.3	1.0	3.7	36.2	18.7	6.1	31.4
5.0	3.1	1.5	4.6	47.6	26.5	11.7	41.3
6.2	3.9	2.0	5.5	58.9	34.3	17.4	51.2
7.4	4.6	2.5	6.5	70.2	42.1	23.0	61.1
8.6	5.4	3.0	7.4	81.6	49.8	28.6	71.0
9.8	6.2	3.5	8.3	92.9	57.6	34.3	80.9
11.0	7.0	4.0	9.2	104.2	65.4	39.9	90.8

the increasing uncertainty above 8 Mg ha^{-1}, this model is most suitable for sites with low to moderate 100-h loads (< 8 Mg ha^{-1}).

We developed three models of large downed wood consumption, and all of them exhibited wide prediction intervals with increasing pre-burn biomass. This common pattern is to be expected because observations of high pre- and post-burn biomass are somewhat less common than low biomass site and there is also more room for variability in higher biomass sites. Due in part to uneven distributions in SLDW and also a weaker correspondence to 1000-h fuel moisture, the SLDW model has poor fit and particularly broad prediction intervals. The RLDW model has much better fit. However, a pre-burn biomass value of 50 Mg ha^{-1} exerted strong leverage; the model would have been weaker without that single observation. The 58 comparison observations of pre-burn biomass and consumption are well within the distribution of our dataset and suggest that our sampled range is generally representative of other sites. Due to increasing model uncertainty at higher biomass values and because large wood can be a dominant fuel category in western pine sites, we recommend that model error be reported along with predicted consumption.

The western litter consumption model has pre-burn litter biomass and duff fuel moisture as predictor variables and has a reasonable model fit. Mean consumption is lower on western than southern pine sites (59% versus 74%) and is negatively correlated with duff fuel moisture. Litter fuel moisture was surprisingly not a significant predictor. As with the southern pine litter consumption model, a potentially important consideration is that prescribed burns may have been patchy, thereby reducing consumption of the litter layer. Where prescribed fires are uniformly continuous, our model may underestimate litter consumption. As with many of the other models reported in this study, prediction intervals widen with increases in pre-burn biomass. The western litter consumption model, in particular, becomes increasingly uncertain with increasing pre-burn litter biomass, as suggested by the wide upper prediction interval in this model, which could result in unexpected smoke impacts.

The wide range of western duff consumption observations contribute to relatively wide prediction intervals, particularly at higher pre-burn biomass values; only two observations had a pre-burn biomass > 45 Mg ha^{-1}, and in both cases, percent duff consumption was higher than average western duff consumption. In contrast, comparison data suggest that consumption is generally much lower than our model predicts. Because duff can comprise a high proportion of pre-burn fuel biomass, the uncertainty in modeled duff consumption can also influence estimates of total site consumption; model uncertainty should be highlighted in sites with high duff biomass. For example, on a site with 25 Mg ha^{-1} of pre-burn duff biomass with an average duff fuel moisture content (53%), our duff consumption model would predict 11 Mg ha^{-1} of consumption with a 95% prediction interval between 0.4 and 21.5 Mg ha^{-1} (Table 4).

5. Conclusions

Models developed by our consumption studies in southern and western pine sites will be incorporated into the latest version of the Consume software application and may also be used in other applications for estimating wildland fuel consumption and emissions in comparable forest types and burning prescriptions. Consumption models by fuel category allow for an estimation of the relative contributions of fuels (e.g., fine downed wood vs litter vs large downed wood vs duff). For site-specific smoke dispersion issues, focusing on pollutant sources, such as large downed wood or duff consumption may be important in the development of burn prescriptions to limit consumption of specific fuels to reduce emissions production and smoke impacts (Ottmar, 2014). The consumption models also include 95% prediction intervals and can be used to estimate uncertainty in regional carbon flux assessments and emissions inventories.

Although empirical models have been used in fuel consumption and wildland fire emissions modeling for decades, they have definite limitations. First, they are constrained by the nature of the observations upon which they are based. Models reported in this study are limited to southern and western pine systems within the measured range of pre-burn loadings, as well as weather conditions typical of prescribed burning in their respective regions and ecosystems. Second, in most of the models we developed, uncertainty increases with pre-burn biomass. We therefore suggest that these models be used to estimate consumption for sites with pre-burn biomass falls within the range of our data and that model uncertainty is reported along with predicted consumption.

Rapid developments are being made with physics-based, fluid-dynamics models of fire behavior. Two models that have been developed in North America include FIRETEC (Linn et al., 2007; Linn et al., 2013) and the Wildland-urban-interface Fire Dynamics Simulator (WFDS; Mell et al., 2007). Both models resolve solid and gas-phase combustion processes at fine spatiotemporal scales. They require high-resolution, three-dimensional fuels data and are computationally expensive. However, they offer a promising new development in fire behavior and combustion modeling and where high-resolution, gridded fuels data are sampled, will likely offer a substantial refinement to simpler models of consumption, such as those presented in this study.

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Appendix A. Supplementary materials

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2017.09.025.

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