

Evaluation of the CONSUME and FOFEM fuel consumption models in pine and mixed hardwood forests of the eastern United States

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Abstract: Reliable predictions of fuel consumption are critical in the eastern United States (US), where prescribed burning is frequently applied to forests and air quality is of increasing concern. CONSUME and the First Order Fire Effects Model (FOFEM), predictive models developed to estimate fuel consumption and emissions from wildland fires, have not been systematically evaluated for application in the eastern US using the same validation data set. In this study, we compiled a fuel consumption data set from 54 operational prescribed fires (43 pine and 11 mixed hardwood sites) to assess each model's uncertainties and application limits. Regions of indifference between measured and predicted values by fuel category and forest type represent the potential error that modelers could incur in estimating fuel consumption by category. Overall, FOFEM predictions have narrower regions of indifference than CONSUME and suggest better correspondence between measured and predicted consumption. However, both models offer reliable predictions of live fuel (shrubs and herbaceous vegetation) and 1 h fine fuels. Results suggest that CONSUME and FOFEM can be improved in their predictive capability for woody fuel, litter, and duff consumption for eastern US forests. Because of their high biomass and potential smoke management problems, refining estimates of litter and duff consumption is of particular importance.

Key words: fuel consumption, model validation, CONSUME, FOFEM, eastern United States.

Résumé : Des prédictions fiables de consommation des combustibles sont essentielles dans l'est des États-Unis (É.-U.) où le brûlage dirigé est souvent utilisé en forêt et où la qualité de l'air est une préoccupation croissante. Les modèles de prédiction CONSUME et FOFEM ont été conçus pour estimer la consommation des combustibles et les émissions associées aux feux de forêt, mais ils n'ont pas été systématiquement évalués pour être appliqués dans l'est des É.-U. en utilisant le même ensemble de données de validation. Dans cette étude, nous avons compilé un ensemble de données de consommation de combustibles à partir de 54 brûlages dirigés opérationnels (43 pinèdes et 11 stations de forêt feuillue mélangée) pour estimer l'incertitude associée à chaque modèle et leurs limites d'application. Les zones d'indifférence entre les valeurs mesurées et prédites par catégorie de combustibles et par type forestier représentent l'erreur potentielle que les modèles pourraient engendrer en estimant la consommation de combustibles par catégorie. Dans l'ensemble, les prédictions de FOFEM ont des zones d'indifférence plus étroites que CONSUME ce qui indique que la consommation prédite serait plus près de la consommation réelle. Cependant, les deux modèles produisent des prédictions fiables des combustibles verts (arbustes et végétation herbacée) et des combustibles fins à durée de séchage d'une heure. Les résultats indiquent qu'on peut améliorer le pouvoir de prédiction de CONSUME et de FOFEM pour la consommation des combustibles ligneux, de la litière et de l'humus pour l'est des É.-U. Étant donné leur biomasse élevée et les problèmes de gestion de la fumée qu'ils pourraient engendrer, il est particulièrement important de raffiner l'estimation de la consommation de la litière et de l'humus. [Traduit par la Rédaction]

Mots-clés : consommation des combustibles, validation de modèles, CONSUME, FOFEM, est des États-Unis.

Introduction

Fuel consumption, defined as the amount of biomass that is fully combusted during a fire, is one of the critical components for estimating (i) wildland fire emissions (Hardy et al. 2001; Urbanski et al. 2011), (ii) effectiveness of prescribed fire in reducing fuel loading (Agee and Skinner 2005; Peterson et al. 2005; Brockway et al. 2005), (iii) amount of heat released, and (iv) numerous other fire effects such as soil heating and potential tree mortality (Reinhardt 2003; Butler and Dickinson 2010). Reliable predictions

of fuel consumption are especially needed in the eastern region of the United States (US) where prescribed burning is widely used, particularly in the southeastern US, for fuel reduction and ecological restoration (Wade and Lunsford 1989; Brockway et al. 2005; Marshall et al. 2008; Waldrop et al. 2009). The continued expansion of the human settlement into wildland–urban interface necessitates reliable smoke production estimates from prescribed burns to ensure air quality compliance, maintain roadway visibility for motorist safety, and protect public health, in areas with

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high population density (Theobald and Romme 2007; Zhang et al. 2008; Goodrick et al. 2010).

CONSUME and the First Order Fire Effects Model (FOFEM) were developed to provide a reliable and efficient means for predicting fuel consumption during wildland fires throughout the US. Although fuel consumption can be measured directly, fieldwork costs are often prohibitive, and most managers rely on fuel consumption models for prescribed burn and smoke management planning and permitting. CONSUME is a software application that contains empirically derived models for estimating fuel consumption, heat release, and pollutant emissions from wildland fires for specific fuel components (e.g., shrubs, herbaceous vegetation, downed wood by size class, litter, and duff) in the boreal, western, and southeastern regions of the US (Prichard et al. 2007; Joint Fire Science Program 2009). Equations used to estimate fuel consumption in southeastern US sites are summarized in Supplementary Table S1.¹ CONSUME also contains semiempirical equations to predict fuel consumption from broadcast burning in recent logging slash that were not evaluated in this study (Prichard et al. 2007). Currently, CONSUME does not include consumption models specific to eastern mixed hardwood forests but uses fuel consumption equations developed from consumption studies in pine forests of the western US as substitutes.

FOFEM (Reinhardt et al. 1997; Reinhardt 2003) is another software application that is widely used for different regions in the US to predict fuel consumption, pollutant emissions, soil heating, and postfire tree mortality. FOFEM uses empirically derived regression models based on region to estimate shrub and duff consumption and assumes that 100% of herbaceous and litter fuels are consumed (Supplementary Table S1). Downed wood consumption in FOFEM is estimated using BURNUP, a process-based model of woody fuel combustion that predicts heat transfer and burning rates of woody fuel particles by size class (Albini and Reinhardt 1995, 1997; Albini et al. 1995; Reinhardt and Dickinson 2010; Lutes 2013).

Predictive models in CONSUME and FOFEM represent our best available methods for modeling fuel consumption in the eastern US. Because both models are empirically based, they are limited in their application and may not fully encompass the broad range of environmental conditions and fuel complexes that are burned in the region. For example, data used to develop the models in CONSUME were collected on dormant-season burns in pine sites and may not adequately represent consumption under growing-season conditions. In addition, because source data used to develop the models in CONSUME and FOFEM were collected from prescribed fires, fuel moisture (FM) and weather conditions associated with wildfires are likely not well represented by these models.

A number of studies have been conducted on wildland fuel consumption in the eastern US (Hough 1968, 1978; Clinton et al. 1998; Scholl and Waldrop 1999; Sparks et al. 2002; Sullivan et al. 2003; Loucks 2004; Kolaks 2004; Goodrick et al. 2010; Reid et al. 2012; Wright 2013). Empirical consumption models developed by Hough (1968, 1978) are still used in FOFEM for predicting shrub and duff consumption in southern pine fuel beds. Clinton et al. (1998) reported fuel consumption from prescribed burns in a single eastern white pine – hardwood site. Scholl and Waldrop (1999) created a photo series with pre- and post-burn fuel loads for a range of loblolly and longleaf pine stands in the Atlantic coastal plain. Sparks et al. (2002) reported fuel consumption values for a shortleaf pine – grassland assemblage. As part of a burn severity study in longleaf pine stands, Sullivan et al. (2003) reported fuel consumption values by fire severity class. Loucks (2004) and Kolaks (2004) both reported fuel consumption in mixed hardwood

sites of the eastern US. Goodrick et al. (2010) reported total fuel consumption in loblolly and longleaf pine forests. Reid et al. (2012) collected surface fuel consumption data in pine clayhills in northern Florida and southern Georgia and compared their results with FOFEM predictions. They found that FOFEM's assumption of 100% consumption of litter and herbaceous fuels overpredicted fine fuel consumption in their sites and recommended that these assumptions be calibrated to actual measurements. Wright (2013) reported fuel consumption for 31 prescribed fires in pine flatwood sites and used the same data collection techniques as were used in this study. Because of the variability in sampling methods, data collection, site locations, and burn conditions, many of these published data sets are unsuitable for fully evaluating consumption models. With the exception of Wright (2013), consumption was not measured for every fuel category compared in this study, and different sampling methods and study designs prevented the inclusion within our validation data set.

The objective of this study was to compile a consistent fuel consumption data set, including pre- and post-burn fuel characteristics, day-of-burn fuel conditions (i.e., FM content), and weather measurements, to (i) assess each model's uncertainties, biases, or application limits and (ii) inform the development of new predictive models of fuel consumption in eastern US forests. A total of 54 operational prescribed fire sites (43 in pine forests, 11 in mixed hardwood forests) are part of this study and were burned between December and April from 2004–2010 (Fig. 1).

Methods

Study areas

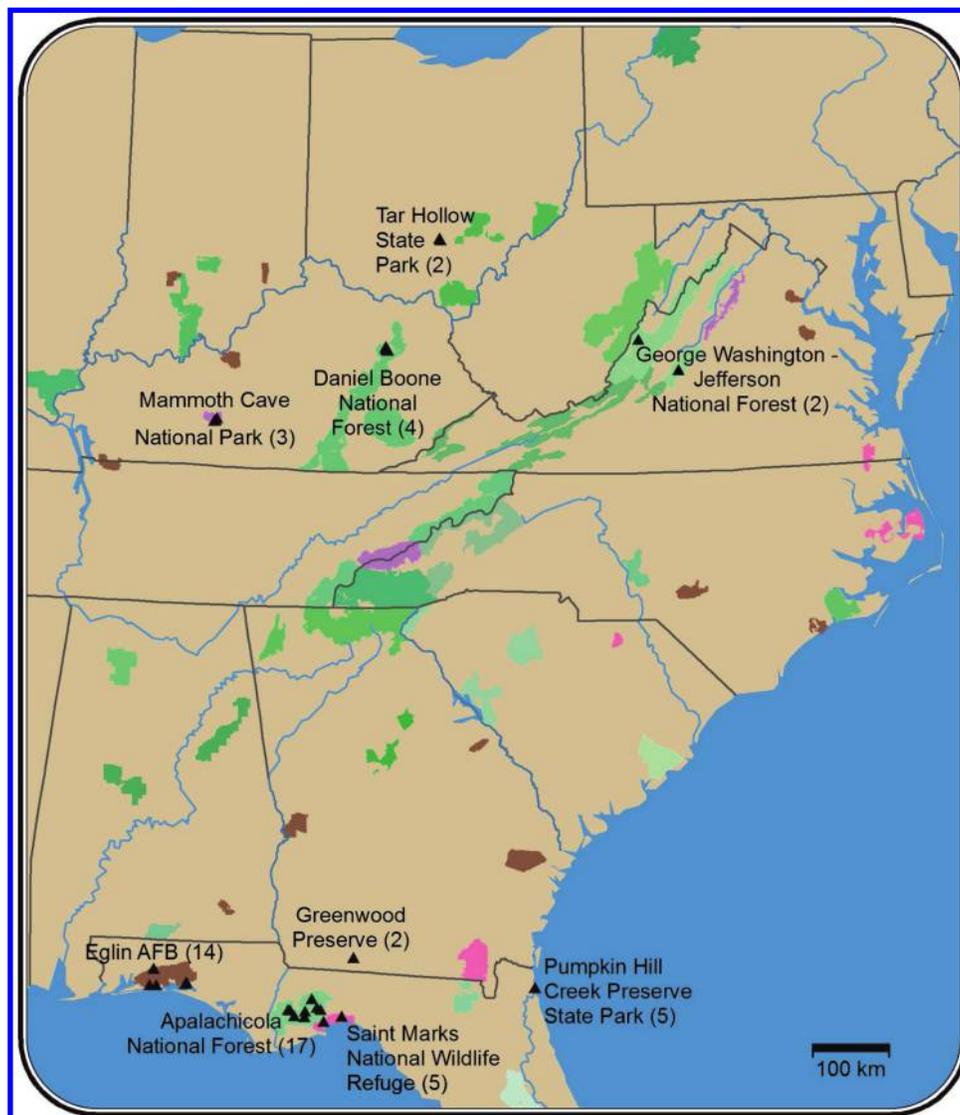
Thirty-eight prescribed fires were sampled in forest types dominated by longleaf (*Pinus palustris* Mill.) and loblolly pine (*P. taeda* L.) with saw palmetto (*Serenoa repens* (Bartr.) Small), gallberry (*Ilex glabra* A.Gray), oak (*Quercus* spp.), shiny huckleberry (*Vaccinium myrsinites* Lam.), dwarf huckleberry (*Gaylussacia dumosa* (Andrews) A.Gray), wiregrass (*Aristida stricta* Michx.), and broomsedge (*Andropogon* L. spp.) understories in Florida, Georgia, and South Carolina (Supplementary Table S2). These sites are regularly burned on a 2- to 3-year rotation. Five additional sites were sampled in pond pine (*Pinus serotina* Michx.) – sand live oak (*Quercus geminata* Small) forests at Pumpkin Hill State Preserve, Florida, that had not been burned in more than 20 years. Climate of southern pine sites is characterized as humid subtropical with mild winters and long growing seasons between 160 and 300 days; temperatures generally range from 0 to 13 °C in January and from 29 to 35 °C in July (Brockway et al. 2005). Of the 43 pine sites, 25 were sampled by Wright (2013) as part of a fuel consumption study in flatwood ecosystems. Eleven mixed hardwood sites were prescribed burned in Kentucky, Ohio, and Virginia. Mixed hardwood sites ranged from open forests with well-developed understories of red maple (*Acer rubrum* L.), dogwood (*Cornus* L. spp.), eastern red-cedar (*Juniperus virginiana* L.), and greenbrier (*Smilax* L. spp.) to closed forests with little to no understory vegetation. Prescribed burns were either hand-ignited with drip torches or ignited by helicopter and typically burned using heading or flanking fires. Burn units ranged from 20 to 600 ha in size. Plots were sampled on a systematic grid within each site, and each plot covered 2–3 ha in size, including woody fuel transects. The number of plots per site varied, but there were generally at least nine preburn and nine postburn plots.

Field measurements

Consumption was measured by collecting pre- and post-burn biomass. Surface fuel biomass and other fuel characteristics were collected using a combination of destructive and nondestructive

¹Supplementary data are available with the article through the journal Web site at <http://nrcresearchpress.com/doi/suppl/10.1139/cjfr-2013-0499>.

Fig. 1. Location of the 54 fuel consumption validation study sites in the eastern US.



sampling methods. Alternating pre- and post-burn clip plots were systematically arranged along two transects with 7.6 m spacing between plots and a minimum of 10 m between transects. Fuels were collected or clipped at ground level within a nested square plot frame. Shrub biomass was collected within a 4 m² plot, and all other biomass was collected within a 1 m² subplot nested within the larger plot. Sampled fuels were separated into the following categories: grasses, forbs, live and dead shrub material, dead and down wood by particle size class (1 h ≤0.6 cm, 10 h = 0.6–2.5 cm, 100 h = 2.5–7.6 cm, 1000 h ≥7.6 cm), and litter (Wright 2013). Duff was absent or minimal in most pine sites and was not sampled in the Pumpkin Hill sites.

Material was oven dried to a constant mass (100 °C for a minimum of 48 h) and weighed or, if too bulky to return to the laboratory, weighed in the field and adjusted to reflect oven-dry mass by using moisture content subsamples that were representative of the field-weighted material. Downed wood >2.54 cm in diameter was rare in regularly burned pine sites, so these particles were inventoried along two 76.2 m planar intercept transects (Brown 1974) per inventory plot. In mixed hardwood sites where downed wood was more abundant, all size classes were inventoried along two random azimuth, 20 m planar intercept transects that originated from one corner of each sampling plot. Across all sites, fuel

consumption of large logs (>7.6 cm diameter) was estimated by measuring proportional diameter reduction of each sampled log. On sites with numerous large logs, 20 logs were randomly sampled for fuel consumption measurements. Preburn circumference was marked with steel wire wrapped around each selected log, and circumference reduction was measured by pulling each wire tightly around the remaining portion of the log. Circumference reduction was converted to proportional diameter reduction under the assumption that each log was round in cross section. Large wood consumption was calculated as the product of proportional reduction of large wood and preburn biomass.

Litter and duff consumption was estimated by measuring depth reduction for mixed hardwood sites. At each site, litter and duff depths were measured at 20 locations arranged on a systematic grid. At each location, sixteen 15 cm long steel nails were inserted through the litter and duff layers into the mineral soil and positioned so that the head of the nail marked the top of the preburn litter layer (Beaufait et al. 1977). Reductions in litter and duff depth were estimated as the average depth reduction of all of the measurement points that burned, multiplied by the proportion of the overall area that burned. Preburn depth and postburn reduction were converted to biomass by multiplying each measured depth by litter and duff bulk density. A minimum of 10 litter and

duff samples of known volume were collected at each site, oven dried to a constant mass (100 °C for a minimum of 48 h), and weighed to determine bulk density.

Sites were burned during the course of operational prescribed burns, which were hand ignited with drip torches or from a helicopter with delayed aerial ignition devices deployed with a plastic sphere dispenser. On the day of each burn, field personnel assisted with burn operations as needed and made observations of within-unit weather and fire behavior during the period when the site was actively burning. Day-of-burn FM samples were collected, and weather variables were measured immediately prior to ignition of each prescribed burn. Three to five samples each of litter, duff, fine woody fuel by size class, grass, and shrub material were collected in heavy-gauge resealable plastic bags, weighed within 4–8 h after collection, oven dried to a constant mass (100 °C for at least 48 h), and reweighed to determine FM content. Where logs were present, FM of >7.6 cm diameter logs (i.e., 1000 h FM) was determined by removing a 3 cm thick disc from all logs that were wrapped with wire to measure large woody fuel consumption.

Model parameterization

To represent the fuel and environmental conditions for each prescribed burn, we used sampled data as input parameters to CONSUME version 4.1 and FOFEM version 5.9. Inputs common to both models include herbaceous, shrub, 1, 10, 100, and 1000 h downed wood biomass and 10 h, 1000 h, and duff FM content. Additional CONSUME inputs include an estimate of the percentage of the burn area blackened by the prescribed burn (“percent black”), litter depth (cm), percent cover of litter, litter arrangement (normal), duff derivation (upper), and duff percent cover (Supplementary Table S3). We used CONSUME’s default western fuel consumption equations to predict mixed hardwood consumption.

Additional FOFEM inputs include forest cover type, season of burn (winter or spring), duff depth, duff biomass, litter biomass, and percentage of rotten logs. Default FOFEM settings include region (southeast for pine sites, northeast for hardwood sites), fire type (moderate), and consumption (natural fuel).

In some cases, there were missing input variables for both models, generally because of an absence of a particular fuel category, which required the use of proxy inputs for the models to run. At sites for which 1000 h FM measurements were not available, a calculated average of 97% was used. Average 1000 h FM was calculated from all sites with reported 1000 h FM (excluding E807D, which had unusually high FM). A value of 50% percent black was used for the site DB_WSLF (Supplementary Table S2). In four sites (GWJ_JR, GWJ_CM, MBGH, and A34), the measured duff moisture content was higher than the FOFEM maximum input value; therefore, the nearest acceptable value was used.

Data analysis

CONSUME and FOFEM were used to predict consumption of the following fuel components: herbaceous vegetation, shrubs, downed wood (1, 10, 100, and ≥ 1000 h size classes), litter, and duff using our sampled fuel loading and moisture input parameters. For each fuel category, we plotted predicted consumption versus measured consumption and conducted ordinary least squares regression to evaluate basic goodness of fit and trends in model residuals. Model evaluation is based on model residuals, which we express as predicted values minus measured values. A positive residual means the model overpredicted the measured value, and a negative residual means that the model underpredicted the measured value. Model bias is evaluated using boxplots and scatterplots of residuals.

We characterized model uncertainty using the paired *t* test for equivalence (Robinson and Froese 2004; Robinson et al. 2005) on the model residuals to estimate a “region of indifference” for predicted consumption relative to measured consumption. If the

predicted values follow the measured consumption very closely, then this region of indifference is narrow, implying small errors, low model uncertainty, and low model bias. If the predicted values do not follow the measured consumption very closely and exhibit strong bias, then the region of indifference is broad, implying large errors and high model uncertainty. The region of indifference is akin to a confidence interval about the model error; a broader interval corresponds to higher model error and a narrower interval to lower model error.

The paired *t* test for equivalence is designed to test the null hypothesis that the predicted and observed are dissimilar ($H_0: \mu_p - \mu_m \neq 0$, $H_1: \mu_p - \mu_m = 0$; μ_p = mean predicted, μ_m = mean measured) given a specified region of indifference, where the region of indifference is comparable with the allowable error in the model. If the null hypothesis is rejected in the equivalence test, then it can be assumed that the model errors fall within the allowable error and the model is deemed adequate. The procedure for conducting the equivalence test is described in Robinson and Froese (2004) and Robinson et al. (2005), and for the equivalence test, we used the `ptte.data` function in the equivalence package in the R Environment for Statistical Computing (Robinson 2013).

No model is able to exactly replicate measured values, and for different model applications, there may be different standards for how large the distance between modeled and measured values can be for the model to still be considered useful. For the consumption models evaluated in this study, we perform the paired *t* test for equivalence for increasing regions of indifference to find the region of indifference for which the null hypothesis of dissimilarity is first rejected. This allows a model user to determine if the region of indifference for a given consumption variable is too wide for their application, or if it is narrow enough to provide an estimate sufficient for decision making and planning. The model users can set their own allowable limit for model error and use the results of this study to determine if the model is within that allowable limit and acceptable for the application, or outside the allowable limit and not acceptable for the application.

To determine the width of the region of indifference at which the null hypothesis of dissimilarity is first rejected, we iterated through values for the region of dissimilarity ranging from 0.05 to 5 Mg·ha⁻¹ with steps of 0.05 Mg·ha⁻¹. Above values of 5 Mg·ha⁻¹, the equivalence test gave inconsistent results, so if the null hypothesis of dissimilarity was not rejected by 5 Mg·ha⁻¹, then the model is considered absolutely inadequate for that variable for any project. These values can then be used by model users to decide whether the model is appropriate for a given project. For example, if a prescribed burn planner made the determination that consumption of the litter layer should be predicted within 0.5 Mg·ha⁻¹, and the region of indifference for litter reported in this study is greater than 0.5 Mg·ha⁻¹, then the planner would not be advised to use the model to predict litter consumption. If the region of indifference reported in this study is less than 0.5 Mg·ha⁻¹, then the model is suitable for the application.

Results

Prefire fuel and fuel consumption

Total surface biomass for the pine sites ranged from 4.6 to 27.0 Mg·ha⁻¹ (Supplementary Fig. S1). Preburn surface fuels in pine sites were dominated by shrubs with a mean of 4.4 ± 2.8 Mg·ha⁻¹, downed wood with a mean of 2.6 ± 2.6 Mg·ha⁻¹, and litter with a mean of 5.2 ± 3.1 Mg·ha⁻¹ (Supplementary Tables S4 and S5). Pine sites contained only a minor herbaceous component, and duff was not sampled (Supplementary Fig. S1a). Mixed hardwood sites had substantially higher preburn surface biomass than the pine sites (22.4 to 96.2 Mg·ha⁻¹). Preburn fuels in mixed hardwood sites were dominated by large woody material with a mean of 31.83 ± 17.3 Mg·ha⁻¹, litter with a mean value of 3.9 ± 0.9 Mg·ha⁻¹, and duff with a mean of 3.9 ± 2.1 Mg·ha⁻¹. Herbaceous fuels were generally

absent ($<0.1 \text{ Mg}\cdot\text{ha}^{-1}$) from mixed hardwood sites, and only one site (DBWSLF) had shrub biomass greater than $1 \text{ Mg}\cdot\text{ha}^{-1}$. Despite large differences in preburn biomass, the total mass of fuel consumed was similar between pine and mixed hardwood sites, ranging from 1.3 to $15.7 \text{ Mg}\cdot\text{ha}^{-1}$ in pine sites and from 3.1 to $10.1 \text{ Mg}\cdot\text{ha}^{-1}$ in mixed hardwood sites (Supplementary Fig. S1b). The majority of fuel consumed in pine sites was in the shrub and litter categories, whereas consumption in mixed hardwood sites was dominated by downed wood and litter with a minor contribution from duff.

Model comparison

In pine sites, total consumption was on average 65% ($\pm 20\%$) compared with 58% ($\pm 12\%$) predicted by CONSUME and 70% ($\pm 12\%$) by FOFEM (Table 1). The following sections compare predicted versus measured consumption by each stratum, results of equivalence tests, and model bias. Scatterplots are used to compare consumption predicted by CONSUME and FOFEM versus measured values for pine sites (Fig. 2) and mixed hardwood sites (Fig. 3). A perfect fit between predicted and measured consumption would be reflected in a linear regression with an intercept of zero and slope of one. Regions of indifference (i.e., the range of values at which the null hypothesis of dissimilarity is rejected) are also displayed. Model bias is examined in Fig. 4.

Shrubs

CONSUME and FOFEM predictions of shrub consumption in pine forests are highly correlated with measured shrub consumption ($R^2 = 0.91$ and 0.83 , respectively, with $p < 0.01$) (Table 2). Both model predictions contain significant bias; CONSUME tends to overpredict whereas FOFEM underpredicts shrub consumption (Fig. 4). For pine sites, predicted and measured shrub consumption can be considered statistically equivalent within $\pm 0.9 \text{ Mg}\cdot\text{ha}^{-1}$ for CONSUME and within $\pm 0.7 \text{ Mg}\cdot\text{ha}^{-1}$ for FOFEM. Regression models are not reported for mixed hardwoods because of low sample size, but both models predict much higher consumption than measured values (Table 3).

Herbaceous vegetation

CONSUME and FOFEM both accurately predict herbaceous fuel consumption in pine sites with R^2 values of 0.97 ($p < 0.01$). For pine sites, predicted and measured herb consumption can be considered statistically equivalent within $\pm 0.05 \text{ Mg}\cdot\text{ha}^{-1}$ for CONSUME and within $\pm 0.10 \text{ Mg}\cdot\text{ha}^{-1}$ for FOFEM (Table 2). CONSUME predictions are unbiased, whereas FOFEM has a consistent positive bias. Model evaluations are not reported for mixed hardwoods because only a single site had herbaceous vegetation.

1 h wood

In pine sites, model predictions are highly correlated with measured values with R^2 values of 0.80 for CONSUME and 0.73 for FOFEM ($p < 0.01$). Predicted and measured 1 h wood consumption can be considered statistically equivalent within $\pm 0.10 \text{ Mg}\cdot\text{ha}^{-1}$ for CONSUME and within $\pm 0.05 \text{ Mg}\cdot\text{ha}^{-1}$ for FOFEM (Table 2). CONSUME predictions are positively biased, whereas FOFEM predictions have no statistically significant bias. With the exception of three sites, mixed hardwood sites had much lower consumption than predicted by either CONSUME and FOFEM and low R^2 values (0.54 and 0.58 for CONSUME and FOFEM, respectively). Regions of indifference are wide relative to preburn loading values ($\geq 0.4 \text{ Mg}\cdot\text{ha}^{-1}$) and comparable between models (Table 3).

10 h wood

In pine sites, CONSUME overestimates 10 h fuel consumption with a predicted 86.5% consumption across all sites versus a mean consumption of $27\% \pm 27\%$ (Table 1). CONSUME predictions are significantly correlated to measured values ($R^2 = 0.68$, $p < 0.01$) but contain a significant positive bias and a wide region of indifference ($\pm 0.65 \text{ Mg}\cdot\text{ha}^{-1}$) (Table 2). Relationships between FOFEM pre-

Table 1. Mean, standard deviation (SD), and sample size (n) of measured and predicted percentage consumption by forest type (southern pine and mixed hardwood) and fuel category.

Fuel category		Southern pine			Mixed hardwoods		
		Mean (%)	SD (%)	n	Mean (%)	SD (%)	n
Total	Measured	64.75	20.45	43	18.77	9.07	11
	CONSUME	57.82	12.01	43	42.79	10.40	11
	FOFEM	69.52	14.26	43	26.96	11.21	11
Shrub	Measured	69.55	17.87	43	29.72	46.48	6
	CONSUME	84.82	13.68	43	79.06	16.87	6
	FOFEM	56.93	6.42	43	64.34	18.61	6
Herb	Measured	92.27	18.44	40	0.00	—	1
	CONSUME	92.74	0.00	40	92.74	—	1
	FOFEM	100.00	0.00	40	100.00	—	1
1 h	Measured	73.89	34.87	38	53.75	23.75	11
	CONSUME	100.00	0.00	38	100.00	0.00	11
	FOFEM	44.92	38.74	38	96.73	10.85	11
10 h	Measured	26.84	27.37	43	42.50	21.66	11
	CONSUME	86.50	0.00	43	86.50	0.00	11
	FOFEM	18.07	26.57	43	74.91	33.13	11
100 h	Measured	19.53	29.37	22	23.84	9.19	11
	CONSUME	40.22	0.00	22	78.44	0.00	11
	FOFEM	3.08	6.73	22	28.89	29.73	11
≥ 1000 h	Measured	11.67	24.37	20	3.58	4.70	11
	CONSUME	4.19	1.87	20	34.04	9.46	11
	FOFEM	0.00	0.00	20	0.50	0.79	11
Litter	Measured	74.40	24.44	43	75.26	14.29	11
	CONSUME	31.13	26.45	43	43.25	31.17	11
	FOFEM	100.00	0.00	43	100.00	0.00	11
Duff	Measured	—	—	0	13.95	9.72	11
	CONSUME	—	—	0	0.00	0.00	11
	FOFEM	—	—	0	35.89	26.39	11

dictions and measured values are not significant in pine sites ($R^2 = 0.08$, $p = 0.07$), although they have a narrower region of indifference ($\pm 0.25 \text{ Mg}\cdot\text{ha}^{-1}$) and no significant predictive bias. CONSUME also overpredicts 10 h consumption in mixed hardwood sites; modeled values are not significantly correlated to measured values ($R^2 = 0.23$, $p = 0.13$). In contrast, FOFEM predictions are significantly correlated to measured consumption in mixed hardwood sites ($R^2 = 0.63$, $p < 0.01$) (Table 3) but contain a significant positive bias. Regions of indifference are wide for both models (1.90 and $1.55 \text{ Mg}\cdot\text{ha}^{-1}$ for CONSUME and FOFEM, respectively).

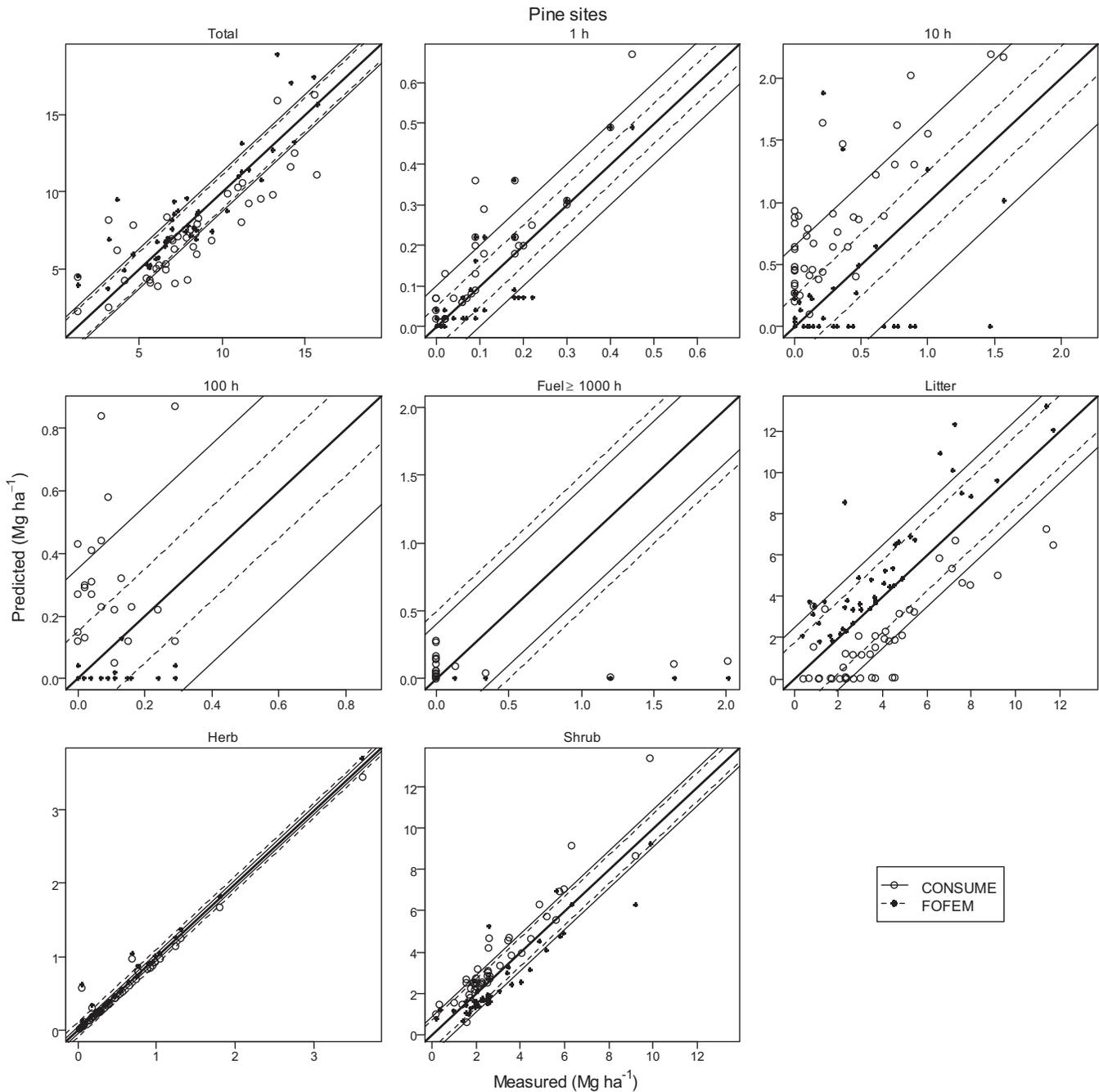
100 h wood

Predicted 100 h consumption for both CONSUME and FOFEM are not significantly correlated to measured consumption in pine sites and have significant bias: CONSUME generally overpredicts and FOFEM underpredicts consumption (Fig. 4). However, regions of indifference are narrow; predicted and measured 100 h wood consumption can be considered statistically equivalent within $\pm 0.2 \text{ Mg}\cdot\text{ha}^{-1}$ for CONSUME and within $\pm 0.1 \text{ Mg}\cdot\text{ha}^{-1}$ for FOFEM (Table 2). In mixed hardwood sites, modeled values are significantly correlated with measured values with an $R^2 = 0.53$ ($p = 0.01$) for CONSUME and $R^2 = 0.73$ ($p < 0.01$) for FOFEM (Table 3). CONSUME consistently overpredicts 100 h consumption, whereas FOFEM predictions have no significant bias. Regions of indifference are wide ($\pm 3.25 \text{ Mg}\cdot\text{ha}^{-1}$ for CONSUME and $\pm 1.1 \text{ Mg}\cdot\text{ha}^{-1}$ for FOFEM).

1000 h wood

As with 100 h fuels, predicted ≥ 1000 h consumption in both CONSUME and FOFEM is not significantly correlated to measured consumption for pine sites (Table 2). CONSUME predicts approximately half as much consumption as was measured, and FOFEM predicts no consumption. Regions of indifference are comparable

Fig. 2. Predicted vs. measured fuel consumption ($\text{Mg}\cdot\text{ha}^{-1}$) in pine sites for total, 1, 10, 100, and ≥ 1000 h wood, litter, herb, and shrub categories. Duff was not present or was negligible in pine sites and was not measured. Open symbols represent CONSUME predictions, and solid symbols represent FOFEM predictions. The solid center black line represents a 1:1 fit (intercept = 0, slope = 1). Points above and below the black line indicate overpredictions and underpredictions, respectively. Regions of indifference for model predictions are represented by solid lines for CONSUME and hatched lines for FOFEM.

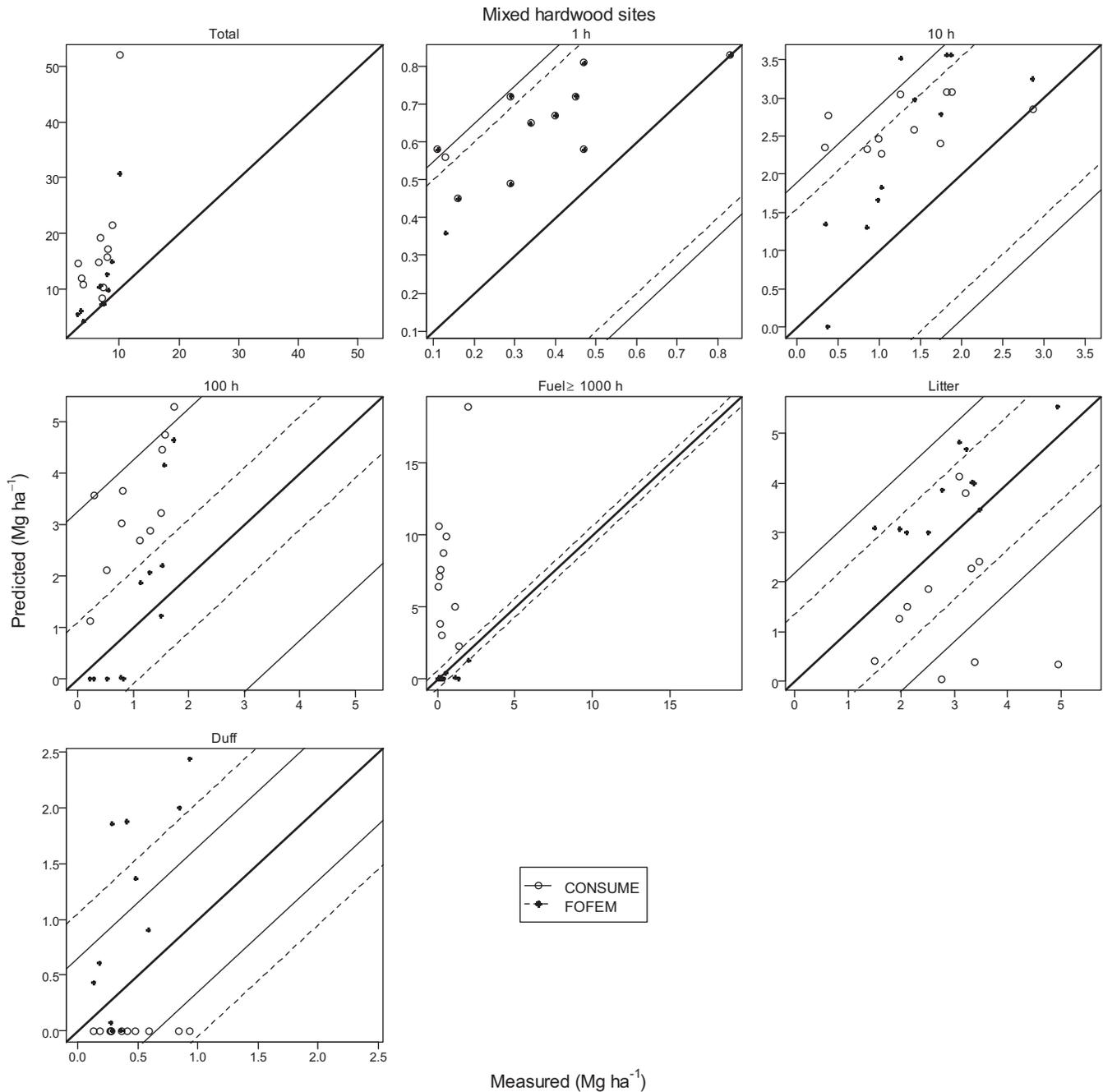


(± 0.20 and ± 0.25 for CONSUME and FOFEM, respectively), and modeled values contain no significant bias. In mixed hardwood sites, CONSUME's predictions are not significantly correlated with measured values and are positively biased, and the region of indifference exceeds the $5 \text{ Mg}\cdot\text{ha}^{-1}$ limit of our equivalence tests (Table 3). FOFEM predictions are significantly correlated to measured consumption ($R^2 = 0.51$, $p = 0.01$), have a significant negative bias, and can be considered statistically equivalent within $\pm 0.65 \text{ Mg}\cdot\text{ha}^{-1}$.

Litter

Predicted and measured litter consumption in pine sites is highly correlated with R^2 values of 0.67 for CONSUME and 0.79 for FOFEM ($p < 0.01$) (Table 2). However, CONSUME generally underpredicts consumption and FOFEM overpredicts consumption with an assumption of 100% litter consumption across all sites. Regions of indifference are wide ($\pm 2.50 \text{ Mg}\cdot\text{ha}^{-1}$ for CONSUME and $\pm 1.75 \text{ Mg}\cdot\text{ha}^{-1}$ for FOFEM). In mixed hardwood sites, there is no significant relationship between CONSUME's predicted litter con-

Fig. 3. Predicted vs. measured fuel consumption ($\text{Mg}\cdot\text{ha}^{-1}$) in mixed hardwood sites for total, 1, 10, 100, and ≥ 1000 h wood, litter, and duff categories. Shrub and herbaceous results are not presented because of low sample size. Open symbols represent CONSUME predictions, and solid symbols represent FOFEM predictions. The solid center black line represents a 1:1 fit (intercept = 0, slope = 1). Points above and below the black line indicate overpredictions and underpredictions, respectively. Regions of indifference for model predictions are represented by solid lines for CONSUME and hatched lines for FOFEM.



sumption and measured values (Table 3). Although FOFEM's predicted values are significantly correlated to measured consumption ($R^2 = 0.69$, $p = 0.02$), predictions are positively biased with an overprediction of litter consumption for 10 of 11 mixed hardwood sites (Supplementary Table S4). Regions of indifference for both models are wide ($\pm 2.20 \text{ Mg}\cdot\text{ha}^{-1}$ for CONSUME and $\pm 1.35 \text{ Mg}\cdot\text{ha}^{-1}$ for FOFEM).

Duff

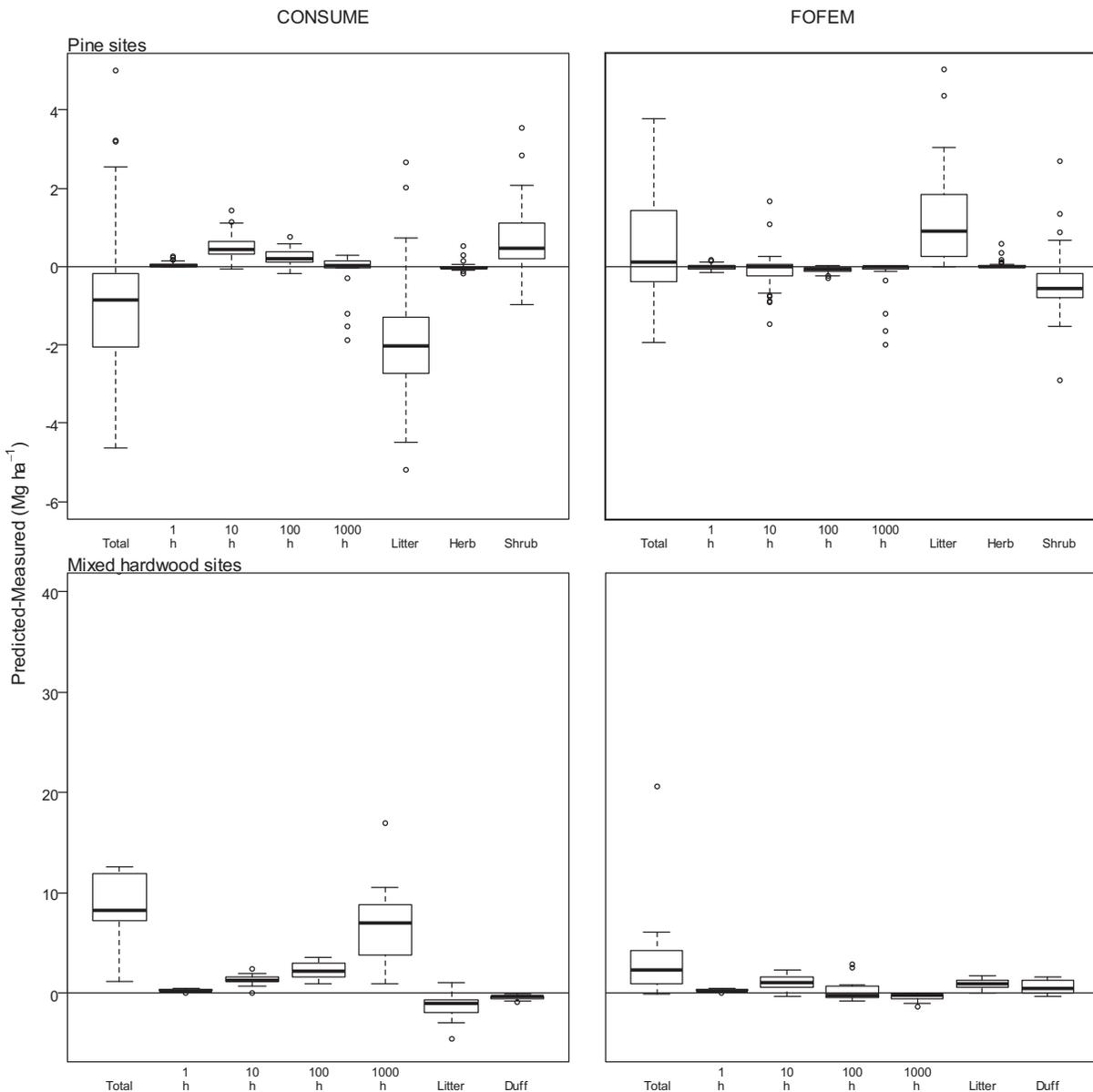
Because of frequent prescribed burning in most pine forest sites, duff consumption was not measured in pine sites. CONSUME

predicted zero duff consumption for all mixed hardwood sites. FOFEM predictions were significantly correlated with measured values ($R^2 = 0.48$, $p = 0.02$) but generally overpredicted consumption and contained significant bias (Table 3).

Discussion

The relative amount of fuel consumption reported in this study is generally comparable with other published studies and suggests that our validation data sets are representative of other southern pine sites and mixed hardwood sites in the eastern US

Fig. 4. Boxplots of residuals (modeled – measured), in $\text{Mg}\cdot\text{ha}^{-1}$, for CONSUME and FOFEM by pine and mixed hardwood sites.



(Table 4). In a study of over 200 prescribed burns in southern pine forests, Reid et al. (2012) reported mean consumption of 84% for herbaceous fuels and 52.3% for litter compared with 92% and 74.4%, respectively, for pine sites in this study. The lower percentage of litter consumption in Reid et al. (2012) could be attributed to differences in preburn litter loading. Sites in the Reid et al. (2012) study had approximately 40% more litter on average than the sites in this study. Grass and fine fuel consumption varies considerably across studies with wide reported standard deviations. Clinton et al. (1998), Scholl and Waldrop (1999), and Sullivan et al. (2003) all report higher percentages of woody fuel consumption than in this study. Percentage litter consumption ranges between 50% and 93% across sites. With the exception of large wood, mixed hardwood consumption reported in this study is comparable with published values in Loucks (2004) and Kolaks (2004); both studies report much higher percentage large fuel consumption (≥ 7.6 cm in diameter) than reported here. Because of the broad diversity found within southeastern pine and mixed hardwood forests, it is not surprising that estimates of fuel consumption vary considerably among studies and sites.

Our model evaluation provides guidance on the potential biases and uncertainty of each model for prescribed fire managers and emissions modelers in the eastern US. In particular, regions of indifference between measured and predicted values by fuel category and forest type represent the potential error that modelers would incur in using each model for estimating surface fuel consumption by fuel category (e.g., shrubs, herbs, downed wood by time-lag class, litter, and duff). Narrow regions of indifference indicate low model uncertainty, whereas wider regions imply greater uncertainty and poorer model performance.

Models used for decision making and planning are often useful in some but not all contexts. It is essential for informed planning that the limits of applicability of models be characterized so that a model user can determine whether a model is appropriate for a given project. The evaluation of consumption models conducted in this study shows for which predictions each model exhibits bias and for which predictions each model exhibits broad regions of indifference. This approach to model evaluation allows the model user to determine if the model uncertainty is too high to be used for a given project, or if the model uncertainty is within the al-

Table 2. Southern pine unit comparisons between predicted and measured fuel consumption for CONSUME and FOFEM including regression statistics and parameters by fuel stratum.

	<i>n</i>	<i>R</i> ²	RMSE	Intercept	Slope	<i>p</i>	Region of indifference (Mg·ha ⁻¹)	Model bias
Shrub								
CONSUME	43	0.9055	0.6378	0.1077	0.7964	<0.0001	0.90	Positive
FOFEM		0.8292	0.8576	0.5082	0.9765	<0.0001	0.70	Negative
Herbaceous								
CONSUME	40	0.9721	0.1081	-0.0220	1.0464	<0.0001	0.05	No bias
FOFEM		0.9717	0.1088	-0.0222	0.9693	<0.0001	0.10	Positive
1 h wood								
CONSUME	36	0.7989	0.0518	0.0021	0.6784	<0.0001	0.10	Positive
FOFEM		0.7327	0.0597	0.0361	0.7161	<0.0001	0.05	No bias
10 h wood								
CONSUME	43	0.6849	0.2252	-0.1957	0.6119	<0.0001	0.65	Positive
FOFEM		0.0758	0.3857	0.2496	0.2583	0.0740	0.25	No bias
100 h wood								
CONSUME	22	0.0228	0.0909	0.0693	0.0630	0.5019	0.20	Positive
FOFEM		0.0340	0.0904	0.0832	0.5642	0.4111	0.10	Negative
>1000 h wood								
CONSUME	20	0.0005	0.6184	0.2813	-0.1631	0.9255	0.20	No bias
FOFEM		0	0.6021	—	—	—	0.25	No bias
Litter								
CONSUME	43	0.6735	1.5619	1.9113	1.0310	<0.0001	2.50	Negative
FOFEM		0.7943	1.2397	-0.1435	0.7793	<0.0001	1.75	Positive

Note: Sample size (*n*) varies depending on the presence or absence of fuel categories. Region of indifference (Mg·ha⁻¹) represents the range of predicted values in which modeled versus actual would still be considered equivalent at $\alpha = 0.05$. Significant model bias (positive, negative, no bias) was determined using paired *t* tests of model residuals. RMSE, root mean square error; *p*, significance of the linear regression model.

Table 3. Mixed hardwood unit comparisons between predicted and measured fuel consumption for CONSUME and FOFEM including regression statistics and parameters by fuel stratum.

	<i>n</i>	<i>R</i> ²	RMSE	Intercept	Slope	<i>p</i>	Region of indifference (Mg·ha ⁻¹)	Model bias
1 h wood								
CONSUME	11	0.5448	0.1458	-0.4323	1.2317	0.0095	0.45	Positive
FOFEM		0.5797	0.1401	-0.2981	1.0523	0.0065	0.40	Positive
10 h wood								
CONSUME	11	0.2322	0.6803	-1.6286	1.1131	0.1334	1.90	Positive
FOFEM		0.6285	0.4731	0.1736	0.4922	0.0036	1.55	Positive
100 h wood								
CONSUME	11	0.5279	0.3899	-0.0617	0.3278	0.0113	3.25	Positive
FOFEM		0.7258	0.2971	0.6375	0.2690	0.0009	1.1	No bias
>1000 h wood								
CONSUME	11	0.1778	0.6126	0.1346	0.0583	0.1964	—	Positive
FOFEM		0.5068	0.4745	0.3607	1.1517	0.0140	0.65	Negative
Litter								
CONSUME	11	0.0050	0.9793	2.8544	0.0474	0.8358	2.20	Negative
FOFEM		0.6884	0.5480	-0.5594	0.9032	0.0016	1.35	Positive
Duff								
CONSUME	11	0	—	—	—	—	—	—
FOFEM		0.4847	0.1965	0.2200	0.2016	0.0173	—	Positive

Note: Region of indifference (Mg·ha⁻¹) represents the range of predicted values in which modeled versus actual would still be considered equivalent. Significant model bias (positive, negative, no bias) was determined using paired *t* tests of model residuals. RMSE, root mean square error; *p*, significance of the linear regression model.

lowable limits for a given project. Results from this study can help modelers decide if and when consumption models from CONSUME and FOFEM may be appropriate for their application. For example, if a prescribed burn planner in a southern pine forest finds that an accuracy threshold as large as 2 Mg·ha⁻¹ is acceptable for predicted litter consumption as long as consumption of shrubs is within 1 Mg·ha⁻¹, then Table 2 shows that FOFEM might be adequate for such a purpose because the regions of indifference for litter and shrubs are less than 2 and 1 Mg·ha⁻¹, respectively. This puts the judgment of model adequacy in the hands of the decision maker who will be using the model and the context for which the model will be used.

Shrub consumption

CONSUME and FOFEM contain empirically based statistical models to estimate shrub consumption that are based on preburn biomass and other variables. CONSUME uses preburn shrub biomass and an estimate of the percentage of the area burned (i.e., percent black), whereas FOFEM employs a regression equation from Hough (1978) with litter and duff biomass, shrub biomass, and duff FM as predictor variables (Supplementary Table S1). Both models have similar goodness of fit and relatively narrow regions of indifference, suggesting that either model is adequate for estimating shrub consumption in pine sites. In a similar analysis,

Table 4. Comparison of percentage consumption (%; \pm SD) by fuel category with other studies.

	Southern pine					Mixed hardwoods		
	This study	Clinton et al. (1998)	Scholl and Waldrop (1999)	Reid et al. (2012)	Sullivan et al. (2003)	This study	Kolaks (2004)	Loucks (2004)
Shrub	70 \pm 18		76 \pm 35			30 \pm 46		
Grass	92 \pm 18		67 \pm 42	84 \pm 21	58 \pm 42			
1 h	74 \pm 35		30 \pm 26		100 \pm 0	54 \pm 24	61 \pm 9	46 \pm 42
10 h	27 \pm 27		100 \pm 0		62 \pm 44	42 \pm 22	41 \pm 22	58 \pm 40
100 h	20 \pm 29		35 \pm 38			24 \pm 9	32 \pm 12	50 \pm 39
1000 h_total	12 \pm 24					4 \pm 5		56 \pm 43
Total wood	28 \pm 24	53 \pm 27	52 \pm 33			12 \pm 7		
Litter (all)	74 \pm 24	50 \pm 16	66 \pm 13	52 \pm 16	93 \pm 16	75 \pm 14	98 \pm 1	67 \pm 32
Duff (all)		18 \pm 15			31 \pm 26	14 \pm 10	25 \pm 8	56 \pm 43

Wright (2013) found that incorporating season of burn in addition to preburn biomass into a shrub consumption model for southern pine fuel types improved prediction accuracy and offers a refinement to the empirical model in CONSUME. Because so few mixed hardwood sites had shrub layers, additional consumption studies in mixed hardwood forests with a shrub component would be needed to evaluate shrub model performance.

Herbaceous consumption

The assumptions of 92.7% and 100% of herbaceous consumption in CONSUME and FOFEM, respectively, provide a reasonable estimate of herbaceous consumption. Extremely narrow regions of indifference indicate strong correspondence between predicted and measured consumption. Actual herbaceous consumption ranged from 51% to 100% with a mean consumption of 92.3%, which is close to CONSUME's empirically based value. Where herbaceous fuels do burn, the amount of consumption typically approaches 100%. Accounting for incomplete burn coverage could potentially produce a more refined estimate of herbaceous fuel consumption in prescribed burn sites where only a fraction of the total area is actually burned. Only one mixed hardwood site contained any herbaceous vegetation, and consumption was measured as zero. As with shrub consumption, additional burns in sites with an herbaceous component would be needed to assess herbaceous consumption model performance in mixed hardwood forests.

Downed wood consumption

Correspondence is high between predicted and actual 1 h fuel consumption in pine sites but substantially lower in mixed hardwood sites. Because the objective of most prescribed burns is to blacken surface fuel layers, an assumption of 100% 1 h fuel consumption could be reasonable in some pine and mixed hardwood sites. However, actual mean 1 h fuel consumption was only 74% for pine sites and 54% for mixed hardwood sites in this study. Development of empirical 1 h downed wood consumption models would refine model estimates. Given that 1 h fuel consumption represents a small fraction of total fuel consumption and regions of indifference are narrow, current model estimates may be sufficient. Sampling error may have contributed to lower model correspondences in mixed hardwood sites because downed wood was surveyed using the planar intercept method rather than fixed-area plots. The litter layer often obscures fine wood during preburn surveys. Where fire intensity is low and duration is short, woody fuels may not fully combust, which can lead to postburn surveys with higher 1 h fuel loads than preburn surveys.

Model performance is generally poor in all other downed wood size classes. Scarcity of wood ≥ 2.54 cm in diameter and discontinuity of downed wood in southern pine sites may contribute to the poor relationship between predicted and actual consumption. Although modeled 10 h consumption is significantly correlated to measured values, CONSUME's simple model of 86.5% consump-

tion of 10 h wood has a significant positive bias. CONSUME tends to overpredict 100 and ≥ 1000 h woody fuel consumption, whereas FOFEM underpredicts 100 h woody fuel consumption and predicts zero consumption of 1000 h woody fuels across all sites. However, depending on the amount of preburn fuel loads in these categories, actual model error may not be high in either CONSUME or FOFEM because regions of indifference in model predictions are quite narrow (<0.25 Mg \cdot ha $^{-1}$).

Although the low sample size in mixed hardwood sites somewhat limits interpretations, FOFEM clearly offers more reasonable predictions than CONSUME. Even so, FOFEM has a significant overprediction bias for 1 and 10 h wood and an underprediction bias in >1000 h wood. The CONSUME western equations appear to be inadequate for application to eastern mixed hardwood forests. Differences in environmental conditions (dry versus humid), FM levels when prescribed burning typically occurs, and fuel types (conifer versus hardwood) may all be responsible to some degree for lack of fit between modeled and measured values and suggest a need for models specific to eastern mixed hardwood forests.

Forest floor consumption

Litter and duff layers, where present, can pose a major smoke management problem. Because of their high bulk densities, litter and duff can represent a high proportion of preburn biomass, and duff, in particular, can contribute to long-term emissions from smoldering combustion (Ottmar 2014). Results from this study suggest that litter and duff consumption models need to be improved in both CONSUME and FOFEM. Estimates of litter consumption differ markedly between the two applications. CONSUME generally underpredicts litter consumption in pine sites and has no significant relationship with measured values in mixed hardwood sites. The litter consumption model in CONSUME is based on input litter depth and tends to underpredict litter consumption with shallow litter depths (<2 cm). FOFEM's assumption of 100% litter consumption offers more reasonable predictions and may be a conservative estimate for smoke management purposes. However, FOFEM overpredicts litter consumption by 25% on average compared with measured values, which could reduce the amount of area permitted for burning. In a study of fuel consumption in southern pine forests, Reid et al. (2012) reported a mean litter consumption value of 54%, which also suggests that FOFEM's assumption of 100% litter consumption is too high for many pine sites. Based on high duff FM in most validation sites, CONSUME predicts zero duff consumption even though measured consumption ranges from 0% to 24% in mixed hardwood sites. FOFEM's predicted duff consumption is significantly correlated to measured consumption but with a significant overestimation bias. As with litter consumption, FOFEM may offer a conservative estimate for prescribed burn and smoke management planning but could reduce the area permitted for burning.

Conclusions

Our validation data set provides a relatively unique opportunity to evaluate how accurately CONSUME and FOFEM predict fuel consumption in eastern forest types. Because independent consumption data sets are rare, this is the first integrated evaluation of CONSUME and FOFEM. This study demonstrates notable differences in model performance among fuel categories and vegetation types. Overall, FOFEM predictions have narrower regions of indifference than CONSUME and suggest better correspondence between measured and predicted consumption values in pine and mixed hardwood sites (Figs. 2 and 3). However, CONSUME and FOFEM both offer reliable predictions of live fuel (shrubs and herbaceous vegetation) and 1 h fine fuels, particularly within pine forests. Model performance is worse in other woody fuel categories. The low number of mixed hardwood sites in our study likely reduced our explanatory power in comparing predicted versus measured values. The BURNUP model within FOFEM appears suitable for predicting woody fuel consumption in sites dominated by woody fuels, as is the case in the mixed hardwood sites.

Overall, we conclude that CONSUME and FOFEM performed quite well for predicted total fuel consumption in the eastern US, considering that both have not been fully parameterized for this important region. However, our results also suggest that CONSUME and FOFEM can be improved in their predictive capability for woody fuel, litter, and duff consumption for the eastern US. Sites with heavy fuel loading or that burn under growing season or extreme fire weather conditions were not included in this study. Additional work is needed to improve the validation data set by targeting sites with high downed wood and forest floor biomass and expanding the number of consumption sites in mixed hardwood forests. Another important consideration for modelers is that consumption models rely on accurate inputs. If managers rely on default fuel loads from either representative fuel beds in CONSUME or default values in FOFEM, model accuracy is likely to be lower than when using measured input values (Reid et al. 2012).

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