

RESEARCH ARTICLE

A CASE STUDY COMPARISON OF LANDFIRE FUEL LOADING AND EMISSIONS GENERATION ON A MIXED CONIFER FOREST IN NORTHERN IDAHO, USA

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ABSTRACT

The use of fire as a land management tool is well recognized for its ecological benefits in many natural systems. To continue to use fire while complying with air quality regulations, land managers are often tasked with modeling emissions from fire during the planning process. To populate such models, the Landscape Fire and Resource Management Planning Tools (LANDFIRE) program has developed raster layers representing vegetation and fuels throughout the United States; however, there are limited studies available comparing LANDFIRE spatially distributed fuel loading data with measured fuel loading data. This study helps address that knowledge gap by evaluating two LANDFIRE fuel loading raster options—Fuels Characteristic Classification System (LANDFIRE-FCCS) and Fuel Loading Model (LANDFIRE-FLM) layers—with measured fuel loadings for a 20 000 ha mixed

RESUMEN

El uso del fuego como herramienta de manejo de tierras es bien reconocido por sus beneficios ecológicos en varios ecosistemas naturales. Para continuar con el uso del fuego y a su vez cumplir con las regulaciones referidas a la calidad del aire, los gestores de tierras deben frecuentemente cumplir con tareas de modelado de emisiones durante el proceso de planificación de las quemaduras. Para alimentar tales modelos, el programa denominado *Landscape Fire and Resource Management Planning Tools* (LANDFIRE) ha desarrollado capas raster, que representan vegetación y combustibles a lo largo de todos los EEUU; desde luego, son limitados los estudios disponibles que puedan comparar los datos de carga de combustibles espacialmente distribuidos derivados del LANDFIRE, con datos similares producto de mediciones de carga de combustible en el terreno. Este estudio ayuda a dilucidar este vacío en el conocimiento mediante la evaluación de carga de combustible usando dos opciones del programa LANDFIRE—el *Fuels Characteristic Classification System* (LANDFIRE-FCCS) y el *Fuel Loading Model* (LANDFIRE-FLM) layers—

conifer study area in northern Idaho, USA. Fuel loadings are compared, and then placed into two emissions models—the First Order Fire Effects Model (FOFEM) and Consume—for a subsequent comparison of consumption and emissions results. The LANDFIRE-FCCS layer showed 200%* higher duff loadings relative to measured loadings. These led to 23% higher total mean total fuel consumption and emissions when modeled in FOFEM. The LANDFIRE-FLM layer showed lower loadings for total surface fuels relative to measured data, especially in the case of coarse woody debris, which in turn led to 51% lower mean total consumption and emissions when modeled in FOFEM. When the comparison was repeated using Consume model outputs, LANDFIRE-FLM consumption was 59% lower relative to that on the measured plots, with 58% lower modeled emissions. Although both LANDFIRE and measured fuel loadings fell within the ranges observed by other researchers in US mixed conifer ecosystems, variation within the fuel loadings for all sources was high, and the differences in fuel loadings led to significant differences in consumption and emissions depending upon the data and model chosen. The results of this case study are consistent with those of other researchers, and indicate that supplementing LANDFIRE-represented data with locally measured data, especially for duff and coarse woody debris, will produce more accurate emissions results relative to using unaltered LANDFIRE-FCCS or LANDFIRE-FLM fuel loadings. Accurate emissions models will aid

comparados con la medición de la carga para 20 000 ha de un área de bosques mixtos de coníferas en el norte de Idaho, EEUU. Las cargas de combustibles fueron comparadas, y luego ubicadas dentro de dos modelos—el *First Order Fire Effects Model* (FOFEM) y el *Consume*—para su subsecuente comparación de los resultados del consumo de combustibles y sus emisiones. El LANDFIRE-FCCS mostró una estimación 200%* superior en la carga del mantillo comparado con la carga medida a campo. Esto llevó a un valor 23% más alto en la media total de consumo y emisiones del combustible cuando fue modelado mediante el modelo FOFEM. El modelo LANDFIRE-FLM layer mostró menores cargas para combustibles de superficie relativo a datos medidos a campo, especialmente en el caso de restos de combustible leñoso grueso (*coarse woody debris*), que a su vez llevó a un 51% menos en el consumo y emisiones promedio cuando fueron modeladas por el modelo FOFEM. Cuando la comparación fue repetida usando el *Consume model outputs*, el consumo estimado por el LANDFIRE-FLM fue un 59% menor en relación a lo determinado en las parcelas medidas, con un 58% menos que las emisiones modeladas. Aunque ambos modelos de LANDFIRE y las cargas efectivamente medidas se ubican dentro de los rangos observados por otros investigadores en los ecosistemas mixtos de coníferas de los EEUU, la variación dentro de las cargas de combustible determinadas por las distintas fuentes fue alta, y las diferencias en carga de combustible llevan a diferencias significativas en consumo y emisiones, dependiendo éstos del modelo elegido. Los resultados de este estudio de caso son consistentes con aquellos obtenidos por otros investigadores, e indican que suplementando datos de LANDFIRE con datos locales obtenidos de mediciones a campo, especialmente para el mantillo y restos de combustible leñoso grueso, producirá resultados de consumo y emisiones más precisos que aquellos que usan solamente datos de carga provistos por LANDFIRE-FCCS o LANDFIRE-FLM. Los modelos de emisiones preci-

*Originally reported as 300%; corrected to 200% on 28 March 2018.

in representing emissions and complying with air quality regulations, thus ensuring the continued use of fire in wildland management.

sos ayudarán a representar emisiones y a cumplir con las regulaciones sobre la calidad del aire, de manera de asegurar el uso continuado del fuego en el manejo de áreas naturales.

Keywords: coarse woody debris, duff, fire effects, fuel loading models, Fuels Characterization Classification System, LANDFIRE

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INTRODUCTION

The use of fire as a land management tool is widely recognized for its ecological benefits, and as a historic disturbance that has driven succession across many ecosystems (Agee 1996, Hardy and Arno 1996, Rothman 2005). While fire science and policy has advanced in the last 50 years to better allow for the use of fire in managing wildlands (van Wagtenonk 2007), increasingly stringent air quality regulations (US EPA 1990, Hardy *et al.* 2001, US EPA 2015,) and an increased awareness of the health impacts from smoke (Liu *et al.* 2015) can make the use of fire as a management tool difficult. In a recent United States survey, prescribed fire practitioners expressed that smoke and air quality issues are the third greatest impediment to prescribed burning, following low work capacity and unfavorable weather conditions (Melvin 2012). To continue using fire as a management tool, land managers must plan to meet management objectives, while also limiting the impact of smoke on public health and keeping smoke levels within regulatory thresholds (NWCG 2014). Such planning may often require the use of models to determine the quantity of emissions generated by fire; these models require many pieces of information, including expected fire size, fuel loading characteristics, and fuel consumption. Of these, fuel loading has been identified as the most critical step in obtaining accurate smoke predictions (Drury *et al.* 2014). Unfortunately,

in many areas there may be little or no measured data on fuel loading; this creates a major difficulty in estimating fuel consumed and emissions produced.

To address the lack of fuel loading information in planning, geospatial Fire Effects Fuel Model (FEFM) layers developed by the Landscape Fire and Resource Management Planning Tools (LANDFIRE) program are often used. LANDFIRE data layers were developed for the contiguous United States, Alaska, and Hawaii to provide consistent geospatial data describing the vegetation type, structure, fuel loading, and disturbances, regardless of land ownership boundaries (Rollins 2009). LANDFIRE is principally intended to inform management and planning decisions made by land management agencies in the United States. It is also the only resource available that provides the geospatial information outlined above across as wide an area as the continental US. To populate models for smoke production, LANDFIRE FEFMs describe fuel loading for duff, litter, woody fuels from timelag size classes ranging from one hour (≤ 0.6 cm) to 1000 hours (≥ 7.62 cm), and live herb and shrub loading. Currently, there are two FEFM choices available through LANDFIRE: one represents fuel loading based on the Fuel Loading Model (FLM) categories developed by Lutes *et al.* (2009), and the other based on Fuels Characteristics Classification System (FCCS) categories developed by Ottmar *et al.* (2007). Both methods are derived

from extensive measured datasets; however, FCCS is stratified to represent fuel loading by vegetation type (Ottmar *et al.* 2007), while FLM is stratified to represent fuel loadings by their potential fire effects (Lutes *et al.* 2009). The two LANDFIRE FEFMs are different not only in how they stratify fuels, but also in their reported fuel loadings.

There have been few studies that detail the differences between these two LANDFIRE FEFMs. One study evaluated their mapping performance across the western United States (Keane *et al.* 2013), and another compared their loadings and resulting emissions as part of a broader comparison of factors affecting smoke predictions in Washington, USA (Drury *et al.* 2014). When Keane *et al.* (2013) compared fuel loading and mapping accuracy of FCCS and FLM LANDFIRE layers throughout the western United States to data from the Forest Inventory and Analysis (FIA) program, they found poor correlations between FIA and LANDFIRE represented loadings, mainly due to the high variability in fuel loadings. Drury *et al.* (2014) compared FLM and FCCS FEFM data with other local datasets and found the landscape fuel loadings to range from 2.7 million Mg to 8.8 million Mg for their research area in Washington, USA, depending on which fuel loading dataset they used.

Studies such as these are extremely valuable for documenting the complexity and variation within fuel loading data, and identifying the importance and challenges of applying FEFM fuels data to model emissions. Our study builds on the few evaluations of LANDFIRE FEFMs to date by comparing FEFM surface fuel loading with measured fuel loadings, and using these loadings in two popular consumption and emissions models—the First Order Fire Effects Model (FOFEM) and Consume—to compare the resulting differences in fuel consumption and emissions production, while holding the site and environmental conditions constant. This provides insight into the degree of fuel loading differences possible

at smaller scales relative to the national or sub-regional scales that LANDFIRE was developed to represent. Yet this 20 000 ha area is large enough to fall within the range of fire management units that land managers are tasked to manage (USDI NPS 2005, USDA FS 2008). We compared duff, litter, herb, shrub, and woody fuel loadings measured in forest inventory plots to those shown on both LANDFIRE Fuel Loading Models (LANDFIRE-FLM) and LANDFIRE Fuels Characterization Classification System (LANDFIRE-FCCS) maps. Subsequent differences in modeled consumption and emissions using FOFEM and Consume are reported.

METHODS

Study Area

To evaluate potential differences in predicted fuel loadings and fire effects, we selected a 20 000 ha study area centered on Moscow Mountain in Latah County, Idaho, USA (Figure 1). The mountain lies in the Palouse Range of northern Idaho, with elevations ranging from 770 m to 1516 m. Moscow Mountain is dominated by mixed conifer forest tree species including ponderosa pine (*Pinus ponderosa* C. Lawson var. *scopulorum* Engelm.), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *glauca* [Beissn.] Franco), grand fir (*Abies grandis* [Douglas ex D. Don] Lindl.), western red cedar (*Thuja plicata* Donn ex D. Don), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and western larch (*Larix occidentalis* Nutt.). Ponderosa pine and Douglas-fir habitat types occur on the xeric southern and western aspects, grand fir and cedar-hemlock habitat types occur on the mesic northern and eastern aspects (Cooper *et al.* 1991). The majority of the land is owned by private timber companies, private non-commercial landowners, and public land holdings. Recent disturbances recorded between 2003 and 2009 were predominantly the result of forest man-

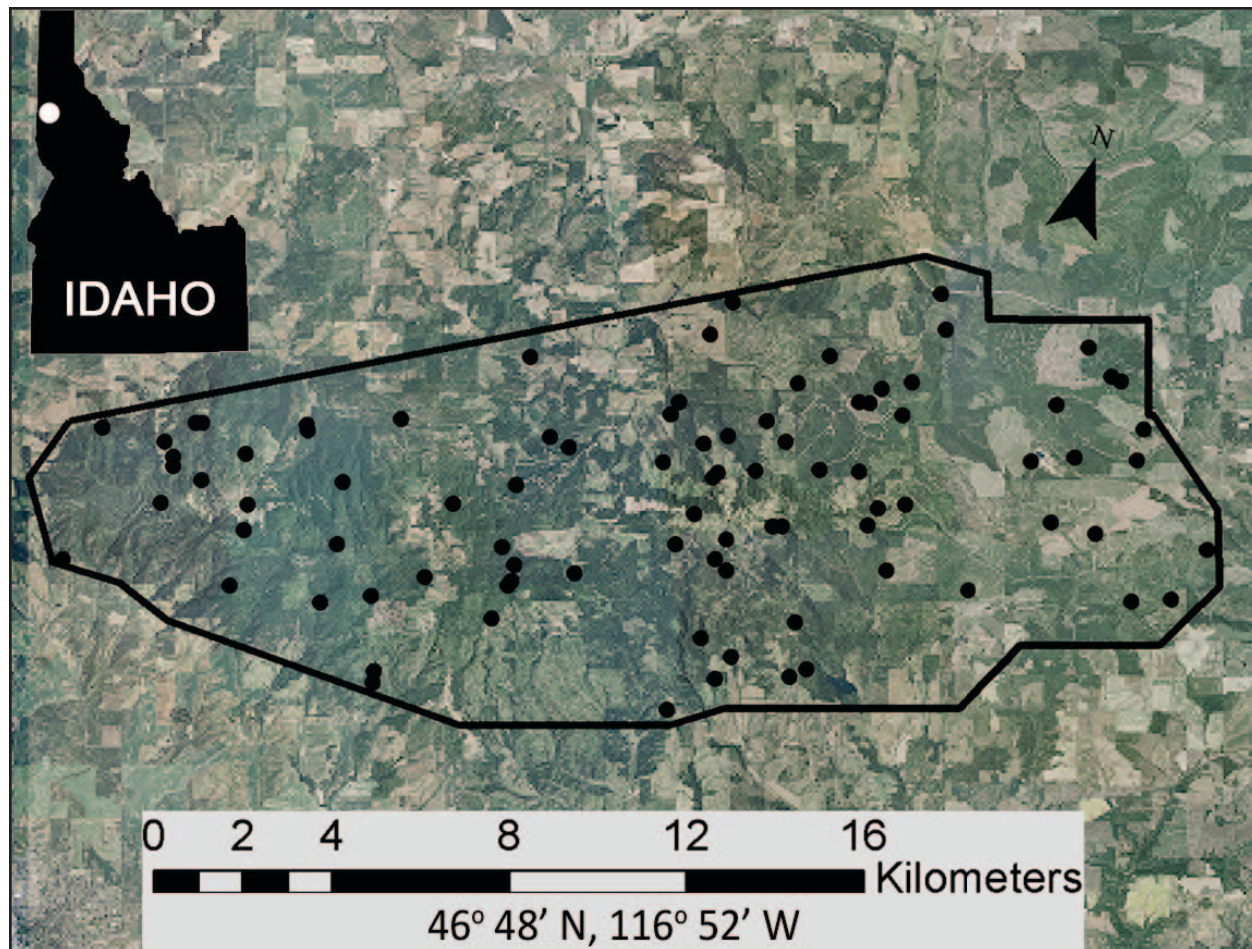


Figure 1. 2009 orthoimagery of the Moscow Mountain, Idaho, USA, study area (outlined) from the United States Geological Survey. The white dot in the inset is the study area. Plot locations are indicated with black dots.

agement practices including thinning, timber harvesting, and prescribed burning (Hudak *et al.* 2012). These activities have resulted in a forest with varying stand ages and structures that occur over a variety of biophysical settings (Falkowski *et al.* 2009, Martinuzzi *et al.* 2009, Hudak *et al.* 2012).

Plot Fuel Loadings

Plot data used in this study were collected in 2009, with information on plot placement and methodologies described in detail in Hudak *et al.* (2012). Following a stratified random sampling design of the study area, 0.04 ha fixed-radius field plots were placed ran-

domly within strata based on elevation, slope, aspect, and percent forest cover. Plots that randomly fell within agricultural areas were subsequently excluded, leaving 87 forested plots for this analysis. Within each plot, duff; litter; coarse woody debris (CWD) in the ≥ 1000 hour (≥ 7.62 cm) size class; and fine woody debris in one hour (< 0.635 cm), ten hour (0.635 cm to 2.54 cm), and 100 hour (2.54 cm to 7.62 cm) size classes were measured and loading was determined as described by Hudak *et al.* (2009), briefly summarized as follows: fuel loading was determined using two parallel 15 m Brown's transects (Brown 1974) centered 2.5 m upslope and downslope from plot center. On each transect,

one hour and ten hour fuels were tallied over a 1.8 m segment, 100 h fuels over a 4.6 m segment, and 1000 h fuels over the entire length of both transects. Shrub and herbaceous cover were estimated ocularly and translated to loadings using equations from Brown (1981) and Smith and Brand (1983). Duff and litter depths were measured once at a set distance along each transect (Brown 1981), and loading was derived from relationships presented in Brown *et al.* (1982) with bulk densities from Woodall and Monleon (2008).

LANDFIRE Fire Effects Fuel Model Loadings

LANDFIRE FEFM map layers are available for both FCCS and FLM fuel classification systems. The FCCS system is composed of fuel loading data organized by vegetation type; each vegetation type is represented by loadings derived from field data collected from that vegetation type (Ottmar *et al.* 2007). FLM fuel loadings are the result of several field-collected datasets, which are grouped into statistically distinct groups based on fuel loading and modeled fire effects (i.e., emissions and soil heating; Lutes *et al.* 2009). In-depth comparisons of these approaches have been addressed by Keane (2013).

For this study, we compared LANDFIRE Refresh 2008 FEFMs to measured fuel loadings. LANDFIRE-FCCS and LANDFIRE-FLM layers were generated using different methodologies. LANDFIRE-FCCS layers were derived by matching FCCS fuelbeds to LANDFIRE vegetation communities (Comer *et al.* 2003) and vegetation type (McKenzie *et al.* 2012, LANDFIRE Team 2014a). LANDFIRE-FLMs were derived by a series of database queries that matched LANDFIRE data to the appropriate FLMs (Hann *et al.* 2012). More specifically, Forest Inventory and Analysis (FIA) data (Woudenberg *et al.* 2010) were keyed to FLMs (Lutes *et al.* 2009) and these FLMs were systematically matched to LANDFIRE vegetation types and cover. We should

note that the scope of our study focuses on the surface fuel loadings represented in LANDFIRE map layers, not the FCCS and FLM fuel classification systems that the layers are intended to represent.

Generating Emissions within FOFEM and Consume

Consumption and emissions were generated using two common fire effects models: Consume version 4.2 (FERA Team 2014) and the Fire Order Fire Effects Model (FOFEM) version 6.0 (Lutes 2012). Consume calculates consumption and emissions based on empirical algorithms from many studies (Prichard *et al.* 2005). The FOFEM model generates consumption based on equations from the BURNUP model (Albini and Reinhardt 1997) and emission factors from Ward *et al.* (1993). Evaluating results in both models is important as FOFEM and Consume are both commonly used in fire management and are integrated into planning tools such as the Interagency Fuels Treatment Decision Support System (IFTDSS 2015). Consume is also integrated into the BlueSky Framework that is used for emissions calculations (AirFire 2015). For this study, we included the major compounds emitted by wildland fire that could be of concern for reasons of human health effects, regulatory impacts, or greenhouse gas emissions: carbon dioxide (CO₂), carbon monoxide (CO), methane (CH₄), and particulate matter 2.5 µm and 10 µm (PM_{2.5} and PM₁₀). Nitrogen oxides (NO_x) and sulfur dioxide (SO₂) were also modeled using only FOFEM, and non-methane hydrocarbons (NMHC) were modeled using only Consume as these options are specific to each model. To parameterize these models we used the values in Table 1 to simulate summer fire conditions under which past fires in the region have ignited (McDonough 2003).

Table 1. Environmental parameters used to populate FOFEM and Consume under default ‘Low’ moisture conditions to simulate an early summer fire.

Parameter	Input
Moistures	
Duff	40 %
10 hour	10 %
CWD	15 %
Soil	10 %
Fuel type	Natural
Region	Interior West
Season	Summer

Statistical Comparison of Fuel Loadings

All analyses were conducted using R Statistical Software (R-Project 2013). We initially tested fuel loading differences using Bartlett’s test for equal variance (Bartlett 1937). This indicated that the data did not meet the assumption of homoscedasticity required for parametric regression analysis. Therefore, we used non-parametric statistical methods. Analysis of variance was chosen and performed using the Anova test from the “car” package (Fox *et al.* 2014) as this version implemented the test using heteroscedasticity-corrected coefficient covariance matrices. If a significant difference was detected, further analysis was

conducted with the Dunnett-Tukey-Kramer pairwise multiple comparison test adjusted for unequal variances and unequal sample sizes (Dunnett 1980) using the DTK package (Lau 2013) at the $\alpha = 0.05$ significance level. This method was used to compare fuel loadings, consumption, and emissions. To examine the influence of different fuels on the total emissions produced, we used Hoffman and Gardner’s Importance Index, a ratio of variances between total emissions generated and each individual fuel component (Hoffman and Gardner 1983, Hamby 1994). Values close to one indicate higher significance than values closer to zero.

RESULTS

Fuel Loadings

In comparing LANDFIRE fuel loadings with measured fuel loadings, all fuel components differed at the $\alpha = 0.05$ significance level with the exception of shrubs (Table 2, Figure 2). LANDFIRE-FCCS loadings over-represented duff and herbs; under-represented litter, 10 h, and 100 h fuels; and did not differ for 1 h fuels or CWD. LANDFIRE-FLM under-represented duff, litter, fine (1 h, 10 h, and 100 h), and CWD fuel loadings; over-represented herb loadings; but duff loading did not

Table 2. Mean fuel loads (Mg ha^{-1} and SD in parentheses) on measured plots and as modeled by LANDFIRE-FCCS and LANDFIRE-FLM. Asterisks indicate statistically significant difference relative to measured loading data at the $P < 0.05$ significance level.

Fuel	Mean plot loading		
	Measured	LANDFIRE-FCCS	LANDFIRE-FLM
Duff	10.55 (10.20)	31.89 (17.80)*	7.76 (12.19)
Litter	5.86 (4.13)	4.199 (1.37)*	3.66 (3.40)*
1 h	0.65 (0.47)	0.81 (0.46)	0.50 (0.32)*
10 h	2.57 (2.19)	1.85 (1.11)*	1.65 (1.13)*
100 h	4.98 (5.20)	2.47 (3.41)*	1.94 (1.66)*
CWD	20.087 (23.33)	18.45 (16.38)	2.75 (4.04)*
Herb	0.46 (0.28)	0.68 (0.76)*	0.73 (0.76)*
Shrub	1.179 (3.08)	1.36 (1.51)	3.65 (10.60)
Total fuel	46.26 (32.49)	61.63 (34.81)*	22.64 (21.16)*

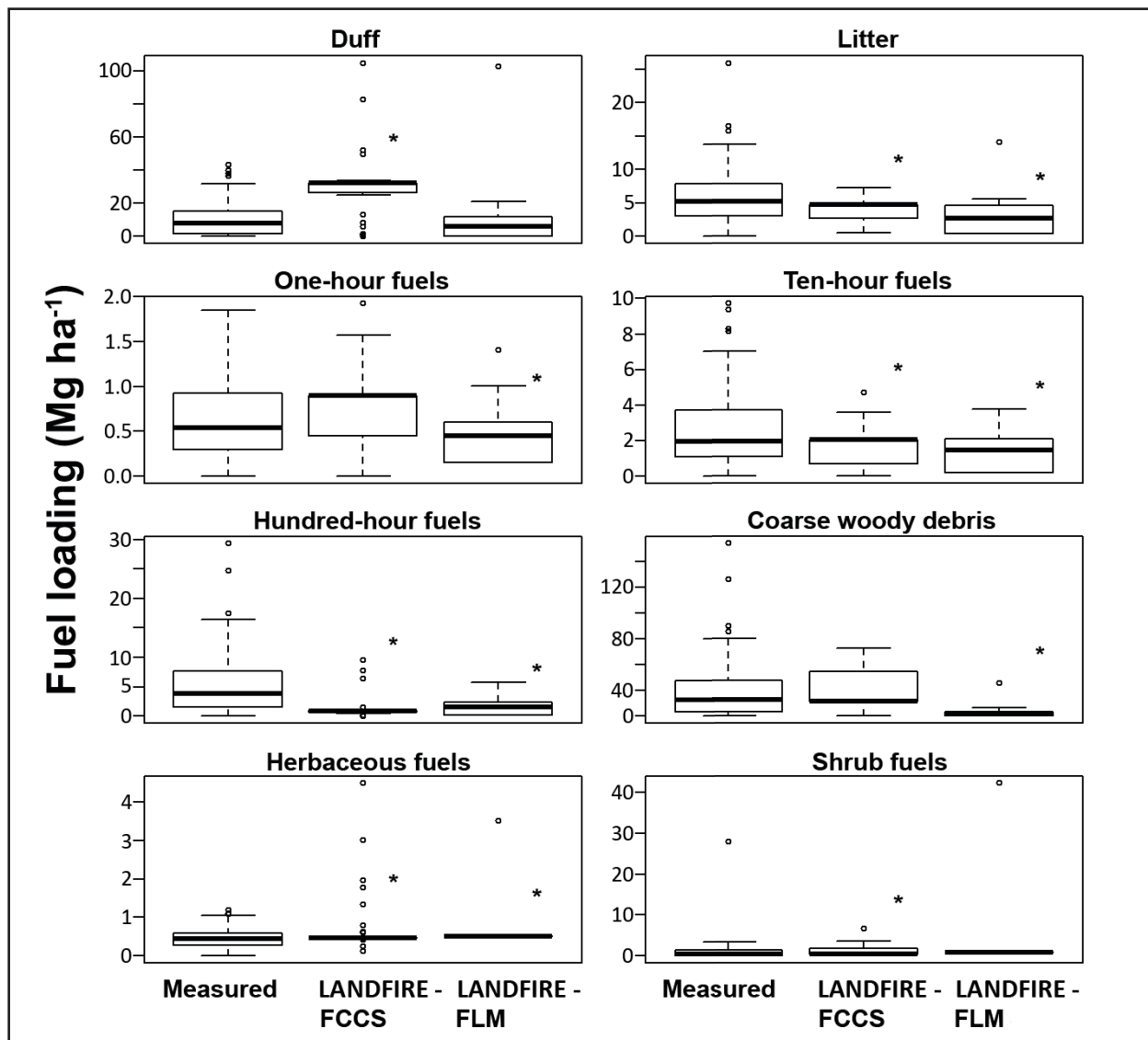


Figure 2. Differences in fuel loading for measured plots, LANDFIRE-FLM, and LANDFIRE-FCCS products. Bold horizontal lines indicate median values, asterisks represent significant differences relative to measured loadings. Circles indicate outliers, and whiskers indicate the region between the first and third quartiles.

differ. Duff and CWD fuel components showed the most pronounced difference in loadings, with LANDFIRE-FCCS duff loadings 200% higher than measured loadings, and 300% higher than LANDFIRE-FLM loadings. LANDFIRE-FLM CWD loading was 9 times lower than measured or LANDFIRE-FCCS loadings. When comparing LANDFIRE FEFMs to each other, only duff, CWD, and 1 h fuel loadings differed, with LANDFIRE-FCCS having the greater loadings.

Modeled Consumption and Emissions in FOFEM

The statistical relationships for fuel consumption mirrored those for fuel loading (Figures 2 and 3, Tables 2 and 3). Relative to measured consumption, the mean total surface consumption from LANDFIRE-FCCS was 23% higher, and LANDFIRE-FLM was 51% lower. It is apparent that the high LANDFIRE-FCCS duff loading led to the higher

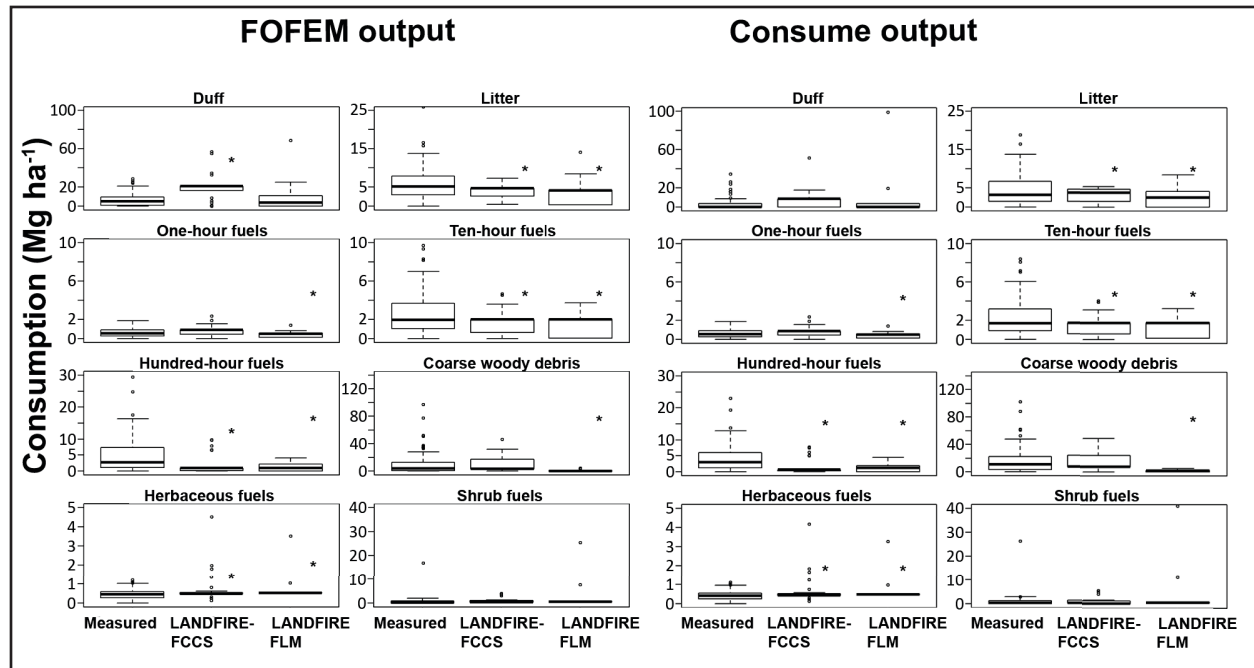


Figure 3. Differences in modeled consumption for measured, LANDFIRE-FLM, and LANDFIRE-FCCS fuel loadings. Bold horizontal lines indicate median values, asterisks represent significant differences relative to results derived from measured loadings.

Table 3. Mean fuel consumption (Mg ha^{-1} with SD in parentheses) under fixed environmental conditions or measured plots, and as modeled by LANDFIRE-FCCS and LANDFIRE-FLM, using FOFEM and Consume. Asterisks indicate statistically significant difference relative to estimates based on measured loadings at the $P < 0.05$ significance level.

Fuel	Mean plot consumption in FOFEM			Mean plot consumption in Consume		
	Measured	LANDFIRE-FCCS	LANDFIRE-FLM	Measured	LANDFIRE-FCCS	LANDFIRE-FLM
Duff	6.98 (6.84)	20.64 (11.66)*	5.35 (8.38)	3.36 (6.48)	5.67 (8.48)	2.31(10.83)
Litter	5.83 (4.16)	4.14 (1.21)*	3.68 (3.23)*	4.45 (3.98)	3.11 (1.66)*	2.32 (1.71)*
1 h	0.65 (0.49)	0.76 (0.44)	0.49 (0.29)*	0.65 (0.49)	0.75 (0.44)	0.49 (0.29)*
10 h	2.58 (2.19)	1.77 (1.17)*	1.62 (1.19)*	2.24 (1.89)	1.53 (1.00)*	1.44 (0.98)*
100 h	4.56 (5.29)	2.32 (3.46)*	1.47 (1.25)*	3.93 (4.06)	1.84 (2.70)*	1.55 (1.30)*
CWD	10.59 (16.88)	8.60 (10.84)	0.53 (0.67)*	17.06 (19.41)	14.20 (14.17)	1.84 (1.56)*
Herb	0.45 (0.28)	0.66 (0.61)*	0.70 (0.70)*	0.42 (0.26)	0.61 (0.57)*	0.64 (0.65)*
Shrub	0.70 (1.85)	0.99 (1.20)	1.99 (5.87)	1.02 (2.88)	1.41 (1.74)	3.10 (9.48)
Total fuel	32.35 (25.46)	39.89 (23.40)	15.83 (14.30)	33.12 (25.90)	29.13 (18.61)	13.69 (16.08)*

overall consumption, and that the low CWD loading in the LANDFIRE-FLM contributed to less consumption. This in turn had a direct effect on the emissions modeled. All modeled emissions, with the exception of NO_x , were significantly higher when modeled using LANDFIRE-FCCS loadings, and lower when

using LANDFIRE-FLM loadings, while emissions derived from measured fuel loadings fell in between (Table 4, Figure 4).

The relative importance of CWD and duff to total emissions was reaffirmed and quantified using the importance index (Table 5). Duff and CWD stood out as the primary con-

Table 4. Mean modeled emissions (Mg ha⁻¹ with SD in parentheses) calculated using FOFEM and Consume for measured plots, LANDFIRE-FCCS, and LANDFIRE-FLM. Asterisks indicate statistically significant difference relative to estimates based on measured loading at the $P < 0.05$ significance level.

Effect	Plot-level values FOFEM			Plot-level values Consume		
	Measured	LANDFIRE-FCCS	LANDFIRE-FLM	Measured	LANDFIRE-FCCS	LANDFIRE-FLM
CH ₄	0.32 (0.30)	0.46 (0.30)*	0.13 (0.14)*	0.19 (0.18)	0.19 (0.14)	0.06 (0.11)*
CO	6.83 (6.56)	10.00 (6.64)*	2.67 (3.00)*	3.67 (3.38)	3.65 (2.65)	1.20 (2.02)*
CO ₂	45.20 (34.09)	52.81 (29.57)	23.39 (21.90)*	51.90 (39.72)	44.82 (28.11)	22.08 (25.22)*
PM _{2.5}	0.53 (0.50)	0.76 (0.50)*	0.22 (0.23)*	0.29 (0.25)	0.27 (0.19)	0.11 (0.15)*
PM ₁₀	0.63 (0.59)	0.90 (0.59)*	0.25 (0.27)*	0.33 (0.28)	0.30 (0.21)	0.12 (0.16)*
SO ₂	0.03 (0.03)	0.04 (0.02)	0.02 (0.01)*			
NO _x	0.03 (0.03)	0.02 (0.01)*	0.02 (0.03)			
NMHC				0.16 (0.14)	0.15 (0.11)	0.05 (0.08)*

tributors to total emissions in all cases, with the exception of LANDFIRE-FLM data, in which duff and shrub loadings were the primary contributors. Although shrub loadings did not statistically differ in our study, shrub loadings tended to be higher in LANDFIRE-FLMs compared to other sources.

Modeled Consumption and Emissions in Consume

With the exception of duff, the relationships between fuel loading and modeled consumption when using Consume remained the same as with FOFEM; modeled duff consumption was much lower when using Consume (Table 3). Duff consumption using LANDFIRE-FCCS loadings did not significantly differ from consumption generated from measured loadings. Because of this, the overall modeled fuel consumption from LANDFIRE-FCCS did not significantly differ from the fuel consumption generated by measured loadings. However, the modeled consumption from LANDFIRE-FLM was significantly lower than consumption from measured loadings, with mean total surface fuel consumption 59% less than that derived from measured fuel loadings.

The importance index for the consumption and total emissions in Consume was similar

to the FOFEM emissions importance index (Table 5). Duff consumption was still an important component with regard to emissions production, even though it did not statistically differ between measured and modeled fuel datasets when modeled with Consume. When emissions were evaluated, the LANDFIRE-FLM generated emissions were significantly lower than those generated using measured fuel loadings. Emissions generated using LANDFIRE-FCCS and measured fuel loadings did not differ from each other (Table 4).

DISCUSSION

Measured Versus Modeled Fuel Loading

Duff and CWD led to the most significant differences in modeled consumption and emissions. LANDFIRE-FLMs contained higher shrub loadings, although this number did not result in a statistically significant difference, nor was it great enough to influence the total surface fuel loading when consumption and emissions were modeled. While the cause for these LANDFIRE-FLM shrub values to be so much higher is not known, the FLM system itself was developed with very little available shrub data (Lutes *et al.* 2009). This likely influenced which FLMs were available to assign

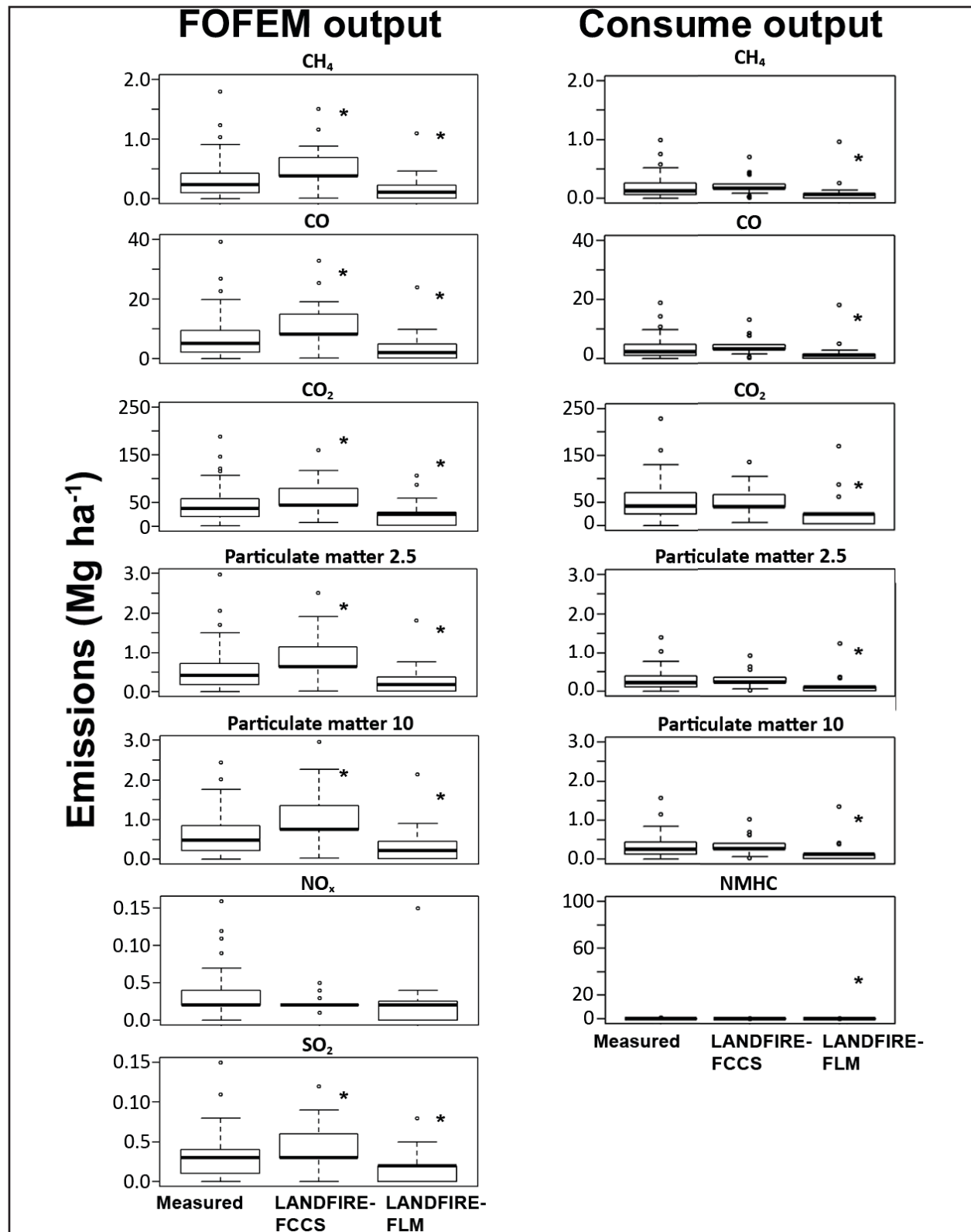


Figure 4. Differences in modeled emissions for measured, LANDFIRE-FLM, and LANDFIRE-FCCS fuel loadings. Bold horizontal lines indicate median values, asterisks represent significant differences relative to results derived from measured loadings.

Table 5. Hoffman and Gardner Importance Index for each FEFM and each fuel type shows that the fuel of relative importance to the total emissions produced varied depending by FEFM. Emissions from measured data and FCCS fuelbeds were most influenced by CWD and duff, and FLM by duff and shrubs, respectively. Highest values are indicated in bold.

Fuel	Importance Index FOFEM			Importance Index Consume		
	Measured	LANDFIRE-FCCS	LANDFIRE-FLM	Measured	LANDFIRE-FCCS	LANDFIRE-FLM
Duff	0.012	0.043	0.053	0.022	0.073	0.0156
Litter	0.002	0.000	0.004	0.008	0.003	0.004
1 h	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
10 h	0.001	<0.001	<0.001	0.002	0.001	0.001
100 h	0.003	0.002	0.001	0.009	0.007	0.002
CWD	0.063	0.048	0.001	0.196	0.204	0.003
Herb	<0.001	<0.001	<0.001	<0.001	<0.001	0.001
Shrub	0.001	0.001	0.032	0.004	0.003	0.119

to LANDFIRE maps when the LANDFIRE-FLM was created. Because the scope of this study focused on a mixed conifer ecosystem, our shrub data were somewhat limited and probably provided little insight in shrub-dominated ecosystems where shrubs are a large fuel component. Further investigation of these LANDFIRE layers in shrub-dominated systems and further fuel loading data from shrub ecosystems would be beneficial to further refining FLMs and the resulting LANDFIRE-FLM data for shrub ecosystems.

When comparing each fuel component for measured and LANDFIRE-represented loadings with those of other mixed conifer systems, all three of our fuel loading sets fell within the ranges observed by other researchers (Table 6). Focusing on duff and coarse woody debris, we found LANDFIRE-FCCS mean duff loading exceeded our measured values, but more closely resembled the ranges found in other mixed conifer forests. Thus, it is possible that our study area may have had less duff loading than other mixed conifer forests. When evaluating mean CWD loadings, we found the wide range noted in other studies, from 0.5 Mg ha⁻¹ to 37 Mg ha⁻¹; LANDFIRE-FLM mean CWD loadings were at the low end of this range averaging 0.53 Mg ha⁻¹, while our measured data and LAND-

FIRE-FCCS were 10.6 Mg ha⁻¹ and 8.6 Mg ha⁻¹, respectively.

Our results support a broader evaluation of the importance of various steps in the emissions modeling process in which Drury *et al.* (2014) compared LANDFIRE-represented loadings to a custom loading map based on measured data. Like our results, their duff loading was higher for LANDFIRE-FCCS relative to loadings represented using measured data, while in our study the LANDFIRE-FCCS total loadings were greater. Drury *et al.* found a wide range in possible fuel loadings depending upon the method chosen, as did we, and concluded that custom fuel loading layers derived from measured data produced the most reliable emissions estimates. Of the two LANDFIRE fuel layers, Drury *et al.* found the LANDFIRE-FCCS layer produced results closer to the custom loading layers. We found this to be true in our study when modeling emissions with Consume, but still found LANDFIRE-FCCS to produce higher emissions values when modeled using FOFEM.

In another study that compared classification, mapping accuracy, and fuel loadings of LANDFIRE-FCCS and LANDFIRE-FLM to Forest Inventory and Analysis (FIA) plot data across the western US, Keane *et al.* (2013) found poor performance in both LAND-

Table 6. Fuel loading for other mixed conifer forests in the western United States compared with mean fuel loading from this study (in Mg ha⁻¹). Standard deviations, when present, are indicated in parentheses. Values from this study are indicated in bold in the last three rows.

Source	Duff	Litter	1 hour	10 hour	100 hour	1000 h sound	1000 h rotten	Herb	Location	Elevation (m)
Hille and Stephens 2005	17.8 (3.6)	17.8 (3.6)	2.0 (0.2)	6.3 (0.7)	5.8 (1.6)	6.0 (3.3)	15.8 (4.3)	-	North-central Sierra Nevada, California	1200 to 1500
Sikkink and Keane 2008			0.019	1.649	0.513	0.683 (sound and rotten)		0.545	NW Rockies*	730 to 2130
Sikkink and Keane 2008			0.012	1.297	0.671	0.549 (sound and rotten)		0.659	NW Rockies	730 to 2130
Sikkink and Keane 2008			0.107	0.709	1.105	0.937 (sound and rotten)		0.581	NW Rockies	730 to 2130
Sikkink and Keane 2008			1.155	4.390	5.682	0.600 (sound and rotten)		0.615	NW Rockies	730 to 2130
Sikkink and Keane 2008			2.586	5.567	7.849	0.863 (sound and rotten)		0.636	NW Rockies	730 to 2130
Youngblood et al. 2008	22.27 (7.52)	5.9 (0.97)	0.94 (0.2)	1.56 (0.33)	4.16 (0.59)	9.63 (3.46)	7.31 (2.5)		Blue Mountain Region, Oregon	1040 to 1480
Youngblood et al. 2008	25.48 (7.03)	3.74 (0.44)	0.37 (0.12)	0.64 (0.21)	3.04 (0.67)	8.88 (4.26)	7.97 (0.61)		Blue Mountain Region, Oregon	1040 to 1480
Raymond and Peterson 2005			1.2	4.1	4.8			1.2	Oregon Coast Range	670 to 850
Raymond and Peterson 2005			4.4	6.8	8.7			1.2	Oregon Coast Range	670 to 850
Kobziar et al. 2006			1.25 (0.87)	4.53 (3.23)	9.93 (8.18)	7.52 (16.82)	14.18 (23.31)		North-central Sierra Nevada, California	1100 to 1410
Kobziar et al. 2006			1.13 (1.04)	5.53 (4.97)	6.17 (7.15)	7.91 (17.04)	29.02 (40.86)		North-central Sierra Nevada, California	1100 to 1410
Kobziar et al. 2006			0.9 (0.71)	2.9 (2.3)	4.25 (4.12)	2.57 (5.36)	26.62 (65.62)		North-central Sierra Nevada, California	1100 to 1410
Reinhard et al. 1991	52 (1.3)		Other values are logging slash, not natural fuels						NW Rockies	900 to 1200
Reinhard et al. 1991	48.4 (1.6)		Other values are logging slash, not natural fuels						NW Rockies	900 to 1200
Measured	10.55 (10.20)	5.86 (4.13)	0.65 (0.47)	2.57 (2.19)	4.98 (5.20)	20.09 (23.33) (sound and rotten)		0.46 (0.28)	NW Rockies	770 to 1516
LANDFIRE-FLM	7.76 (12.19)	3.66 (3.40)	0.50 (0.32)	1.65 (1.13)	2.47 (3.41)	2.75 (4.04) (sound and rotten)		0.73 (0.76)	NW Rockies	770 to 1516
LANDFIRE-FCCS	31.89 (17.8)	4.19 (1.37)	0.81 (0.46)	1.85 (1.11)	1.94 (1.66)	18.45 (16.38) (sound and rotten)		0.68 (0.76)	NW Rockies	770 to 1516

*NW Rockies includes parts of Idaho and Montana, USA.

FIRE-represented FEFMs. LANDFIRE-FLM tended to under-predict loadings while LANDFIRE-FCCS tended toward over prediction. However, LANDFIRE-FLM loadings had lower root mean squared errors (Keane *et al.* 2013). Our findings here support the work of Keane *et al.* (2013) and Drury *et al.* (2014) in describing the tendency of LANDFIRE-FCCS to have higher loadings relative to LANDFIRE-FLMs.

Modeled Consumption and Emissions Using FOFEM

Relative differences in consumption values when modeled with FOFEM mirrored those of the loading values. High LANDFIRE-FCCS duff and low LANDFIRE-FLM CWD loading and consumption contributed to the total modeled emissions being highest when using LANDFIRE-FCCS inputs, and lowest when using LANDFIRE-FLM inputs. In examining the fuel loading data (Table 2), there is high variance in all fuel loading categories. This supports the work by Keane *et al.* (2013), who noted the high variance inherent in all categories of fuel loading, and the difficulties caused by spatial variation when trying to represent fuel loadings across large landscapes. Consumption followed the pattern of the total fuel loading values for the landscape, with LANDFIRE-FCCS being the highest, FLM being the lowest, and measured values in the middle. This in turn produced higher emissions from LANDFIRE-FCCS and lower emissions from LANDFIRE-FLM, highlighting the differences in emissions outcomes depending upon the choices made to represent fuel loadings.

Modeled Consumption and Emissions Using Consume

In comparing consumption and emissions from Consume, the choice of model has an effect on emissions generated. In this study, there were similar trends in modeled consump-

tion with both fire effects models, but the lower duff consumption in Consume, relative to FOFEM, led to emissions outputs in which LANDFIRE-FCCS derived emissions did not differ from those derived from measured loadings. This difference in duff consumption is due to the fact that Consume and FOFEM calculate the consumption of duff using different equations, derived from different data sets (Reinhardt 2003, Prichard *et al.* 2005).

Research Implications

In modeling emissions, fuel loadings have been identified as the most crucial variables (Drury *et al.* 2014), yet they represent one of the greatest uncertainties in modeling emissions (French *et al.* 2011). In a detailed discussion on the topic, Keane *et al.* (2013) identified several factors creating difficulties in quantifying fuel loadings. These include lack of data to develop thorough loading maps; the use of classification systems that were developed from discrete plot locations but then applied to large, national-scale areas; and the inherent difficulty of classifying fuels into categories such as hourly size classes and duff, when each of these size classes may have different degrees of variation at different spatial scales (Keane *et al.* 2012, 2013). If existing fuel loading classification maps are to be improved, more data are necessary. The results of our study indicate that data on CWD and duff should be priorities, due to the relative importance of these fuels to overall emissions in mixed conifer forests (Table 5). While consumption didn't statistically differ for the specific case of shrubs, shrub loading accounted for a great deal of variability in emissions from LANDFIRE-FLMs (Table 5), a classification that was developed with little available shrub data (Lutes *et al.* 2009). For the case of LANDFIRE-FLMs, having additional data on shrub loadings would be beneficial.

Despite being represented at a 30 m resolution, LANDFIRE data layers are intended to

be used at larger, sub-regional to national scales (LANDFIRE Team 2014b). Data from fuel loading maps may work for finer scales; however, there will likely be greater need to supplement that data with local knowledge. Based on our findings in a 20 000 ha area, using measured data, especially for duff and CWD loadings, is preferable relative to unaltered LANDFIRE layers. However, we understand that measured data are often unavailable, may be incomplete, or limited in availability.

Management Implications

If monitoring resources are available, emission estimates will be improved by having more information on duff loading, as differences in duff loading lead to the greatest differences in emissions, followed by CWD. For coarse woody debris, the planar intercept sampling methods have been most commonly used in forests such as in this study, although the Photoload (Keane and Dickinson 2007) method has also performed well (Sikkink and Keane 2008). Duff sampling is often performed via sampling points along a planar intercept to gather both loading and depth (Brown 1974). The fuel photoseries guides available for many ecosystems provide estimates of duff loading (Ottmar *et al.* 2003), but there are few studies comparing their performance relative to the traditional method. If measured data are not available, one could model with both the LANDFIRE-FLM and LANDFIRE-FCCS derived fuel loadings, and then average the two sets of results.

The use of systems such as the Wildland Fire Decision Support System (WFDSS) and the Interagency Fuels Treatment Decision

Support System (IFTDSS) also hold potential for obtaining measured fuel loading information (IFTDSS 2015, WFDSS 2015). These systems provide online access to several models to represent fire behavior and effects (including emissions), but they also provide an easy platform from which data can be shared from user to user. In the future, it would be ideal to see a searchable database of user-provided fuel loadings within these decision support systems, similar to the searchable data available through the Fire Research and Management Exchange System (FRAMES) Resource Catalog (FRAMES 2015).

This study has characterized the potential differences in LANDFIRE-represented fuel loadings in a mixed conifer case study area, and their impact on the emissions modeling. While using measured data provides the most reliable outcome, either by itself or to help supplement the LANDFIRE data, this is not always possible. Web-based systems can aid in finding and sharing data; however, a search for the keywords “duff” and “coarse woody debris” in FRAMES returned 34 and 3 results, respectively. While online systems can be powerful sources of information, there is clearly a need for additional data with which tools such as the LANDFIRE map layers could be strengthened. In the interim, information on the relative differences in fuel loadings from LANDFIRE-represented data may be useful to managers who are tasked with quantifying emissions for fire management planning. Using all of these resources will aid in generating more accurate emissions estimates in a climate where regulatory pressure and the need to accurately represent potential emissions from fire are increasing.

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