INTERCOMPARISON OF FIRE SIZE, FUEL LOADING, FUEL CONSUMPTION, AND SMOKE EMISSIONS ESTIMATES ON THE 2006 TRIPOD FIRE, WASHINGTON, USA

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ABSTRACT	RESUMEN
Land managers rely on prescribed burning and naturally ignited wildfires for ecosystem management, and must balance trade-offs of air quality, carbon storage, and ecosystem health. A current challenge for land managers when using fire for ecosystem management is managing smoke production. Smoke emissions are a potential human health hazard due to the production of fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), and ozone (O_3) precursors. In addition, smoke emissions can impact transportation safety and contribute to regional haze issues. Quantifying wildland fire emissions is a critical step for evaluating the impact of smoke on human health and welfare, and is also required for air quality modeling efforts and greenhouse gas reporting. Smoke emissions modeling is a complex process that requires the combination of multiple sources of data, the application of scientific knowledge from	La gente que está a cargo de la gestión del territorio utiliza quemas controladas e igniciones naturales para el manejo de los ecosistemas y debe de buscar compensar los costos de transacción que emergen entre la protección de la calidad del aire, la captura de carbón y la salud de los ecosistemas. El manejo de la producción de humo es un reto actual para la gestión del territorio con enfoque de ecosistemas. Las emisiones de humo son un peligro potencial para la salud humana debido a la producción de partículas finas ($PM_{2.5}$), monóxido de carbono (CO) y precursores de ozono (O_3). Además, las emisiones de humo pueden afectar la seguridad en el transporte y generar problemas de visibilidad a escala regional. La cuantificación de las emisiones resultantes por fuego es un paso crítico para la evaluación del impacto del humo sobre la salud y el bienestar humano y además es una variable requerida para producir modelos sobre calidad del aire y emisiones de gases de efecto invernadero. La modelización de emisiones de humo es un proceso complejo que requiere la incorporación de

divergent scientific disciplines, and the linking of various scientific models in a logical, progressive sequence. Typically, estimates of fire size, available fuel loading (biomass available to burn), and fuel consumption (biomass consumed) are needed to calculate the quantities of pollutants produced by a fire. Here we examine the 2006 Tripod Fire Complex as a case study for comparing alternative data sets and combinations of scientific models available for calculating fire emissions. Specifically, we use five fire size information sources, seven fuel loading maps, and two consumption models (Consume 4.0 and FOFEM 5.7) that also include sets of emissions factors. We find that the choice of fuel loading is the most critical step in the modeling pathway, with different fuel loading maps varying by 108 %, while fire size and fuel consumption show smaller variations (36 % and 23 %, respectively). Moreover, we find that modeled fuel loading maps likely underestimate the amount of fuel burned during wildfires as field assessments of total woody fuel loading were consistently higher than modeled fuel loadings in all cases. The $PM_{2.5}$ emissions estimates from Consume and FOFEM vary by 37 %. In addition, comparisons with available observational data demonstrate the value of using local data sets where possible.

múltiples fuentes de datos, la aplicación de conocimiento de disciplinas científicas divergentes y la vinculación de varios modelos científicos en una secuencia lógica y progresiva. Típicamente, las estimaciones del tamaño de fuego, cargas (biomasa disponible) y consumo de combustibles resultan necesarios para calcular la cantidad de contaminantes producidos por un fuego. Aquí examinamos el Complejo del Incendio Tripod (Tripod Fire Complex) de 2006 como caso para estudiar bases de datos alternativas y la combinación de modelos científicos disponibles para calcular las emisiones por incendios. Específicamente, utilizamos cinco fuentes para el tamaño de los incendios, siete mapas de cargas de combustibles y dos modelos de consumo (Consume 4.0 y FOFEM 5.7), que también incluyen series de factores de emisión. Averiguamos que la elección de cargas de combustibles es el paso más crítico en la elaboración de modelos, con mapas que varían hasta un 108 %, mientras que el tamaño del incendio y el consumo de combustibles varían menos (36 % y 23 % respectivamente). Encontramos que es probable que los mapas de modelización de cargas de combustibles subestimen la cantidad de combustible consumido durante los incendios, ya que las mediciones reales fueron superiores a las cantidades modelizadas en todos los casos. Las estimaciones de emisiones de $PM_{2.5}$ generadas por Consume y FOFEM varían en 37 %. Las comparaciones realizadas con datos empíricos demuestran el valor de utilizar bases de datos locales cuando sea posible.

INTRODUCTION

Naturally ignited wildfires and prescribed fires play a key ecological role by regulating species composition, forest structure, hazardous fuels, and species regeneration in many wildland ecosystems (Weaver 1951, Cooper 1960, Agee 1998). In fact, following the 1995 Federal Wildland Fire Management Policy and Program Review, many local, state, and federal agencies emphasized the need to re-introduce fire into fire-adapted landscapes in their land management plans (NWCG 2001, Stephens and Ruth 2005). However, smoke emissions from adding more fire to the landscape constitute a potential human health hazard due to the production of harmful pollutants such as fine-grained particulate matter (particles ≤2.5 microns in diameter, or $PM_{2.5}$), carbon monoxide (CO), and ozone (O_3) precursors (Hardy *et al.* 2001, Reinhardt and Ottmar 2004, Larkin *et al.* 2009, Ottmar *et al.* 2009, Koichi *et al.* 2010). Such fires also affect human welfare by contributing to regional haze, reducing visibility, and increasing concentrations of greenhouse gases. Smoke impacts on health and visibility are a growing concern due to the number of severe fire seasons that have occurred since 2000, largely as a result of warmer temperatures, drier environments, and increased fuel loadings from historic fire suppression efforts (Mutch 1994, Ferry *et al.* 1995, Westerling *et al.* 2006). A key challenge for land managers is balancing the need for fire to maintain ecosystem health while managing smoke emissions.

To address potential smoke impacts due to burning, land managers must first understand the magnitude of smoke emitted by wildfires on local, regional, and global scales (Knorr *et al.* 2012). To quantify smoke emissions, land managers have turned to scientific models that are intended to provide reasonable estimates of smoke emitted by biomass burning during both wildfire and prescribed fire events (Larkin *et al.* 2009, Ottmar *et al.* 2009, French *et al.*

2011, Knorr *et al.* 2012). Smoke emissions modeling is a complex process that requires the combination of multiple sources of data, the application of scientific knowledge from divergent scientific disciplines, and the linking of various scientific models in a logical progressive sequence.

Decision support frameworks have been developed to provide modeling pathways that guide users through the complicated smoke emissions modeling process in a series of steps, including (1) identifying fire size and location; (2) determining fuel loadings; (3) estimating fuel consumption; (4) producing realistic estimates of smoke emissions (Figure 1); and, in some cases, (5) predicting smoke plume transport, dispersion, and chemical properties. Examples of such frameworks include the BlueSky Framework (Larkin *et al.* 2009) and the Wildland Fire Emissions Information System (WFEIS; French *et al.* 2011). A variety of data sets and models are available within the framework for performing each step in the modeling pathway (Larkin *et al.* 2009, Goodrick *et al.* 2012, McKenzie *et al.* 2012), and the selection of data sets and models can have a significant impact on the resulting estimates of smoke emissions (N. Larkin, USDA Forest Service, Seattle, Washington, USA, unpublished data; Phase 1 of the Smoke and Emissions Model Intercomparison Project (SEMIP): test cases, methods, and analysis results; http://www.airfire.org/projects/semip).

The Smoke and Emissions Model Intercomparison Project (SEMIP) (N. Larkin. unpublished data) was designed to create an open standard for comparing smoke and emissions models against each other and against real-world observations. In this study, we apply the SEMIP intercomparison methods and framework to the 2006 Tripod Fire Complex, a large fire event that occurred in Washington state, USA (N. Larkin, unpublished data). We intercompare five fire reporting systems, seven fuel loading maps, and two fuel consumption models, which, when combined into a modeling
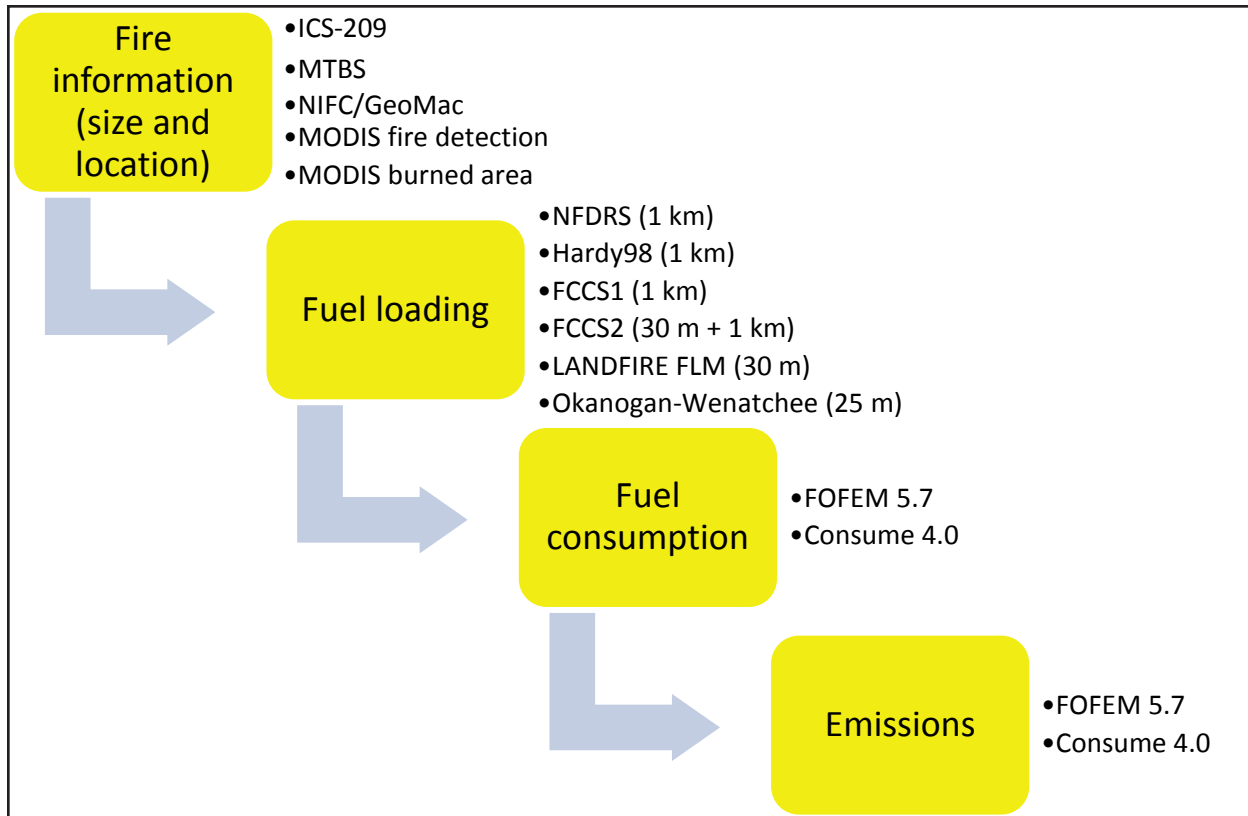
Figure 1. The modeling steps for which intercomparisons were performed for the smoke emissions modeling on the Tripod Fire Complex. The models, or systems, evaluated in this study are listed for each level.

pathway, lead to estimates of fire emissions. The results of each step in the modeling chain (Figure 1) are examined and, where possible, compared to observations. The goal of our study was to evaluate uncertainties in emissions estimates by quantifying the variability in results produced by various modeling pathways at each modeling step. The Tripod Fire Complex event provides a single large fire case study and illustrates how the variability at each modeling step can be quantified for individual fires.

Background

Smoke emissions modeling studies. Three recent papers provide interesting insights into the potential for different outcomes when using models to generate smoke emissions. Ottmar *et al.* (2009) reviewed current knowledge,

data, and types of predictive models commonly used for smoke emissions modeling. Knorr *et al.* (2012) discussed issues surrounding smoke emissions modeling on a global scale. French *et al.* (2011) discussed potential variability in smoke emissions modeling using carbon as a specific pollutant. From this literature, it is clear that uncertainty exists at each step in smoke emissions modeling pathways. Ottmar *et al.* (2009) and Knorr *et al.* (2012) suggest that the largest potential differences are found during the fuel characterization and fuel consumption step when modeling smoke emissions. These authors found large differences in fuel loading and fuel consumption based on vegetation type and fuel classification system. Large differences were also observed in the fire detection and fire size estimates in these studies. The Ottmar *et al.* (2009) review further suggests that reducing

uncertainty in the fuel characterization and fuel consumption steps will reduce uncertainty in smoke emissions modeling across scales (global, national, regional, single fire) and fire types (wildfire or prescribed fire). In the French *et al.* (2011) study, estimates of carbon emissions from wildfires were found to vary regionally. Their study attributed the observed differences in carbon emissions to high variability in fuel loading across regions because modeled emissions were higher in regions with higher fuel loadings. Moreover, French *et al.* (2011) observed high variability in modeled fuel consumption across regions. In some regions, modeled fuel consumption outputs were very similar, while they varied widely in others. French *et al.* (2011) suggested a causal relationship, with higher fuel loadings leading to higher fuel consumption and ultimately higher carbon emissions.

In each of these studies, the observed differences in fire size, fuel loading, and fuel consumption were passed down the modeling pathway to affect the magnitude of modeled emissions outputs. These recent studies have improved our understanding of the complexities involved in modeling smoke emissions, yet the results indicate that the range of uncertainty at each step in smoke emissions modeling pathways must be evaluated further.

The Tripod Fire Complex. Lightning strikes on 3 Jul 2006 and 24 Jul 2006 ignited the Spur Peak Fire and the Tripod Fire in Washington state's Okanogan-Wenatchee National Forest, USA. These fires burned together as the Tripod Fire Complex, one of the largest wildfire events in the state's history. From July until November, the Tripod Fire Complex burned across a range of vegetation types, including grasslands, sage shrublands, Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests, ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) forests, lodgepole pine (*Pinus contorta* Douglas ex Loudon) forests, and mixed-species forests. Fire severity (magnitude of environmental change, Lentile *et al.*

2006) was classified as moderate to high, with reports of the fire spreading as a mixture of variable-intensity crown and surface fires. Low fuel moisture contents and above-average fall temperatures enabled the fire to continue burning until it was extinguished by season-ending snow and rain events.

The size of the Tripod Fire Complex ensured that the event would be captured by numerous fire reporting systems, which made possible comparisons of reported fire location and size information. The multiple vegetation types burned during this large wildfire allowed for comparisons of fuel loading, fuel consumption, and smoke emissions across a range of vegetation types from grasslands to dense high-elevation, closed-canopy forests. In addition, fuels and fuel loadings had been extensively studied in the Tripod area, leading to the availability of several fuel loading maps for use in estimating biomass quantities. Moreover, a series of field-level fuels plots were sampled prior to the fire, allowing for direct comparison among modeled and observed fuel loadings, and post-burn field observations of fuel consumption were also available for comparison with modeled estimates. The availability of these data sources made the Tripod Fire Complex well-suited for evaluating the influence of fire size, fuel loading, fuel consumption, and smoke emissions analyses.

METHODS

We focused on quantifying the impact of selecting various data sets and models for estimating fire size, fuel loading, fuel consumption, and emissions, because these were the most readily quantifiable steps in smoke emissions modeling pathways. The specific data sets and models compared for each of these steps were described.

Fire Size Information

A number of systems are in use by fire management personnel to identify wildfire size

and location. For this analysis, we evaluated fire size information from the following five fire reporting systems (Figure 2):

1. *ICS-209 incident reports*. The ICS-209 report is the official form used to report fire size information for large incidents. These reports (available at http://fam. nwcg.gov/fam-web/hist_209/report_

list_209) provide a set of coordinates indicating the fire ignition point; the spatial extent of the fire must be incorporated from other sources or approximated as a circle drawn from the fire origin point.

2. *Monitoring Trends in Burn Severity (MTBS) maps*. The primary objective of the MTBS project is to provide spa-
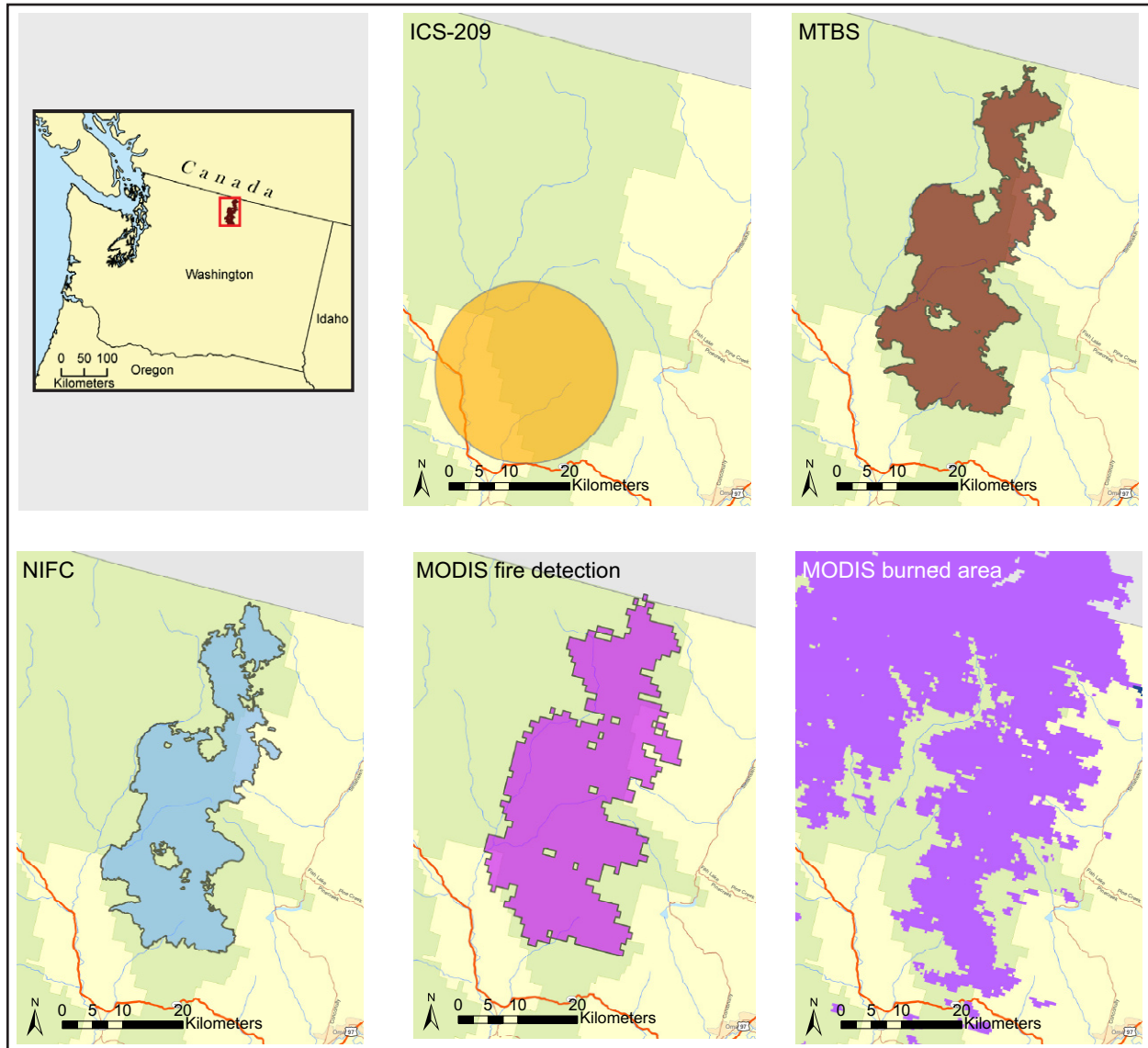

Figure 2. Tripod Fire Complex size and perimeter for each of the five fire reporting systems compared. The ICS-209 reports do not have fire perimeters associated with them; they only report fire size. Therefore, the fire area is represented by a circle, centered on the fire ignition point, that reflects the fire size reported by the ICS-209. The MODIS burned area product assumed that the fire was a snow field and therefore produced a fire size of 0.

tially explicit burn severity information for national analysis of fire severity trends (Eidenshink *et al.* 2007). MTBS maps (available at http://www.mtbs.gov) are produced using pre- and post-wildfire Landsat imagery to identify areas where the landscape burned during wildfires (Eidenshink *et al.* 2007).

3. *NIFC and GeoMac.* The National Interagency Fire Center (NIFC) keeps polygon records of fire perimeters constructed by geographic information system (GIS) specialists assigned to the incident. GeoMac is the interagency storage location for these maps, and the field-mapped perimeters are viewed as the official fire perimeter maps by local land management agencies (R. Harrod, USDA Forest Service, Okanogan-Wenatchee National Forest, personal communication).

4. *Moderate Resolution Imaging Spectroradiometer (MODIS) fire detection.* MODIS uses Terra (AM; morning) and Aqua (PM; afternoon) satellite passes to provide products on fire location, energy emitted, flaming and smoldering ratios, and estimated area (number of pixels) burned (Giglio *et al.* 2009). For the Tripod Fire Complex, fire area was determined by aggregating all pixels detected by the MODIS fire detection product into a single raster file. If fire was detected within an individual pixel, it was assumed that the entire pixel burned.

5. *MODIS burned area.* The MODIS burned area product uses the land surface reflectance data from the Terra and Aqua satellite passes to determine the day of burning for each 500 m^2 pixel. Fire size is estimated by combining all pixels where fire was detected during a particular set of days (Boschetti *et al.* 2009). If fire was detected within an individual pixel, it was assumed that the entire pixel burned.

We mapped fire size (area) perimeters in ArcGIS 9.2 for the Tripod Fire Complex from each of the data sources listed previously, and calculated the area covered by the fire for each reporting system. Percentage difference statistics were calculated for each fire size report using the NIFC fire perimeter as the standard fire perimeter.

Fuel Loading Maps

Fuel loading maps provide estimates of the biomass (fuels) available to burn across landscapes. For the Tripod Fire area, we used seven fuel loading maps to estimate the quantity of biomass available to burn during the fire event.

1. *National Fire Danger Rating System (NFDRS) fire danger fuel model map.* The NFDRS fuel model map provides a spatially consistent map of fuel loadings at a 1 km resolution for the continental United States (Burgan *et al.* 1997*a*, Burgan *et al.* 1998). The mapped NFDRS fuel models include fuel quantity information for live woody fuels (shrubs), herbaceous fuels, and downed and dead woody fuels. NFDRS maps do not include information on larger woody fuels, decomposed (rotten) woody fuels, canopy fuels, litter, or duff.

2. *Hardy98.* The Hardy98 vegetation cover and fuel loading map provides a spatially consistent map of fuel loadings at 1 km resolution for the western United States (Hardy *et al.* 1998). In this map, vegetation cover types comprise 18 broad categories created using an EROS Data Center LAND Characterization Class (USDI Geological Survey, EROS Data Center, Sioux Falls, South Dakota, USA) product. The fuel loadings by vegetation cover type are presented for live shrubs, live herbaceous fuels, downed woody fuels, litter, and duff.

3. *Fuel Characteristic Classification System (FCCS1) original.* The FCCS1 fuel loading map provides fuel loading information at a 1 km scale for the continental United States (McKenzie *et al.* 2007). In the FCCS1 fuel mapping process, one of 112 fuelbeds was assigned to each 1 km pixel in a national map using a rule-based assignment methodology (McKenzie *et al.* 2007). The FCCS fuelbed concept is the most comprehensive of the fuel maps and includes downed woody fuels, shrubs, herbs, grasses, canopy fuels, dead standing trees (snags), stumps, litter, moss, lichens, and duff.

4. *Fuel Characteristic Classification System—Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) crosswalk maps (FCCS2 30 m and 1 km).* We refer to the FCCS-LANDFIRE crosswalk maps as FCCS2 to distinguish them from the original FCCS maps previously described. The FCCS2 30 m map provides standard FCCS fuelbeds and associated fuel loadings mapped at 30 m for the continental United States, Alaska, and Hawaii. The FCCS2 30 m map uses the LANDFIRE map product structure and is available as a LANDFIRE map product. To produce this map, the standard FCCS fuelbeds and LANDFIRE Existing Vegetation Types (EVT) map layer were crosswalked (D. McKenzie, USDA Forest Service, Pacific Northwest Research Station, personal communication). The 1 km FCCS2 map is an aggregated version of the 30 m FCCS2 map (McKenzie *et al.* 2012).

5. *LANDFIRE Fuel Loading Models (FLMs).* The LANDFIRE FLM map product provides fuel loading values for surface fuels at 30 m resolution across the continental United States (J. Herynk, Systems for Ecosystem Management,

personal communication). The FLMs were produced from 4046 field plots where shrubs, herbs, downed woody fuel, litter, and duff were measured and classified into fuel loading models based on expected emissions (Lutes *et al.* 2009, Sikkink *et al.* 2009).

6. *Okanogan-Wenatchee National Forest FCCS custom fuelbeds map (OkWen custom FCCS).* The OkWen fuelbed map consists of a set of 83 custom FCCS fuelbeds mapped at 25 m resolution across the Okanogan-Wenatchee National Forest. The map was created by linking custom fuelbeds to a set of Forest Service vegetation layers (McKenzie *et al.* 2007).

To intercompare fuel loading maps, we prepared vegetation maps for each fuel loading data source. Additional maps were created for each fuel strata (total fuel loading, surface fuel loading, canopy, shrubs, herbaceous, woody fuels, duff, and litter) and for each of the fuel loading maps. We calculated summary fuel loading statistics (minimum, first quartile, median, third quartile, maximum) in megagrams per hectare for each fuel map, and calculated relative differences (with FCCS2 1 km set as the reference map for coarse scale fuel loading maps and FCCS2 30 m serving as the reference map for fine scale fuel loading maps) to identify potential variability across the landscape by data source.

Fuel Consumption

Fuel consumption modeling systems estimate fuel consumption on the level of tree stands (Reinhardt and Dickinson 2010). Spatial assessments of fuel consumption during a single large wildfire event can be estimated using the fuel loading maps discussed previously. In addition to total fuel consumption, a time profile estimate of fuel consumption by phase (flaming, smoldering, and residual) is also con-

sidered because the quantity and mixture of emissions varies by phase.

We used the First Order Fire Effects Model (FOFEM) 5.7 and Consume 4.0 fuel consumption models to calculate fuels consumed by the Tripod Fire Complex. FOFEM (Reinhardt *et al.* 1997, Reinhardt and Dickinson 2010) and Consume (Prichard *et al.* 2006) contain fuel consumption algorithms that estimate fuel consumption based on fuel loading (fuel available to burn) and fuel condition (moisture of fuels, fuel state). Consume 4.0 is the Python recoding of Consume 3.0, completed by the Michigan Technical Research Institute, Ann Arbor, USA.

To model fuel consumption, FOFEM and Consume require a standard set of inputs, including fuel loading data, fuel moisture by fuel type (e.g., 10 hr, 100 hr, duff), and the percentage of canopy consumed and area blackened. In addition, we developed fuel moisture inputs to the models using the Wildland Fire Assessment System (WFAS; Burgan *et al.* 1997*b*) and the Fire Emissions Prediction Simulator (FEPS; Anderson *et al.* 2004). The WFAS produces and maps daily estimates of 10 hr, 100 hr, and 1000 hr fuel moisture content for the continental United States, Alaska, and Hawaii. For the period and location of interest, WFAS consistently estimated 1000 hr fuel moisture at 8 %. Because WFAS does not provide daily estimates of duff fuel moisture, and daily estimates of 10 hr fuel moisture varied greatly over the time period studied, we used

an existing default FEPS fuel moisture lookup table (Table 1) to determine duff and 10 hr fuel moisture values that correspond to a 1000 hr fuel moisture value of 8 %. We set the duff and 10 hr values to 25 % and 6 %, respectively.

We ran Consume and FOFEM on each of the seven fuel loading maps to identify variability in fuel consumption resulting from model choice. We set the inputs for each model to reflect a severe wildfire, and we set canopy consumption to 60 %. For Consume to calculate shrub consumption, we set percentage blackened to 95 %.

We summarized and plotted the FOFEM and Consume outputs by fuel loading map to evaluate fuel consumption variability. Summary statistics, including digital maps of percentage difference and the minimum, first quartile, median, third quartile, and maximum values, were calculated.

Emissions Modeling

FOFEM 5.7 and Consume 4.0 estimate smoke emissions by applying emission factors to fuel consumption estimates (Ward *et al.* 1993). Emission factors are empirically derived algorithms that quantify the production of gases and particulates by the fire, including total particulate matter, $PM_{2.5}$, particulate matter ≤ 10 microns in diameter (PM_{10}), CO, carbon dioxide (CO_2), methane (CH_4), sulfur dioxide (SO_2), oxides of nitrogen (NO_x), and non-methane hydrocarbons (NMHC).

Table 1. Default fuel moisture profiles from the Fire Emissions Prediction Simulator (FEPS).

	Fuel moisture profiles (percent moisture)					
	1 hr	**10 hr**	**100 hr**	**1000 hr**	**Live**	**Duff**
Very dry	4	6	8	8	60	25
Dry	7	8	9	12	80	40
Moderate	8	9	11	15	100	70
Moist	10	12	12	22	130	150
Wet	18	20	22	31	180	250
Very wet	28	30	32	75	300	400

FOFEM 5.7 estimates emissions of PM_{10}, $PM_{2.5}$, CO, CO_2, CH_4, NO_x, and SO_2 using a set of default emission factors (Table 2; Ward *et al.* 1993, Hao 2003). Default combustion efficiencies of 0.97 for the flaming phase and 0.67 for the smoldering phase are used to determine the proportions of fuel consumed during each phase. Proportions of fuel consumed during flaming and smoldering are determined using Burnup, the combustion physics model in FO-FEM (Albini and Reinhardt 1995).

Consume 4.0 provides several alternative emission factors for modeling smoke emissions. For the fuels burned during the Tripod Fire Complex, we estimated smoke emissions using the Consume default emission factors (Table 2); these settings are commonly used for modeling fuels across landscapes. The Consume default emission factors are averages of all emission factors in Consume for natural fuels and are assigned by fuel type (Douglas-fir, mixed conifer, ponderosa pine, hardwood, juniper (*Juniperus* spp.), and sagebrush (*Artemisia* spp.), and consumption phase (flaming, smoldering, and residual smoldering) (Prichard *et al.* 2006). Consume estimates emissions for total particulates, PM_{10}, $PM_{2.5}$, CO, CO_2, CH_4, and NMHC, and reports emissions separately for the flaming and smoldering stages of burning (Prichard *et al.* 2006).

We compared smoke emissions for each of the seven fuel loading maps by producing plots of pollutant-specific emissions estimates generated by each model, including plots of relative differences between model pathway results. We also compared smoke emissions across fuel loading inputs to identify potential influences of fuel loadings on later steps in the smoke emissions modeling pathway. In all cases, we compared emissions estimates for the five pollutants common to both FOFEM and Consume: CO, CO_2, CH_4, $PM_{2.5}$, and PM_{10}.

Observational Data

The Okanogan-Wenatchee National Forest provided observational plot data from the late 1990s from the Pacific Northwest Current Vegetation Survey (CVS; Johnson 2001; E. Peterson, USDA Forest Service, Okanogan-Wenatchee National Forest, personal communication). The CVS woody fuels data provided direct observations to compare with modeled fuel loading data from each fuel loading map. We summarized the CVS woody fuel data four

Table 2. Emission factors used, by pollutant type (kg Mg^{-1}).

| | Consumption model | | | |
| | FOFEM 5.7 | | Consume 4.0 | |
Pollutant	Flaming combustion	Smoldering combustion	Flaming combustion	Smoldering combustion
$PM_{2.5}$	2.5	22.5	6.5	9.5
PM_{10}	3.0	26.5	7.5	12.0
PM			11.5	17.0
CO	6.5	301.5	45.0	104.5
CO_2	1778.0	1228.0	1261.0	1142.5
CH_4	1.0	14.0	1.5	5.5
SO_2	1.0	1.0		
NO_x	3.0	0.0		
NMHC			2.5	5.0

size classes (10 hr, 100 hr, 1000 hr, and total woody fuels). We calculated the biomass available to burn for each size class following Brown (1974). We intercompared the modeled and observed woody fuel loadings using box and whisker plotting techniques (Wilkinson 1982).

We linked MTBS satellite observations of burn severity (unburned, low, moderate, high) to field estimates of fuel consumption from Justice *et al.* (2010). When coupled with composite burn indices (CBI) that feature field estimates of fuel consumed in burn areas (Key and Benson 2006), MTBS burn severity maps can be used to provide a remotely sensed estimate of fuel consumption across landscapes. For the Tripod Fire Complex, Justice *et al.* (2010) coupled CBI methodology with post-fire field sampling of vegetation and fuels data to produce indices relating fuel consumption to MTBS burn severity. In our study, we used the Tripod fuel consumption indices provided by Justice *et al.* (2010) and the mapped MTBS burn severity classes for the Tripod Fire Complex to produce a composite map of observed fuel consumption estimates across the Tripod Fire Complex burn area.

Modeling Pathways

To evaluate potential differences in smoke emissions due to alternative fire information data, fuel inputs, fuel consumption modeling, or alternative smoke emissions computation, we analyzed model output at each level in the modeling pathway (Figure 1). We compared fire size for each of the five fire reporting systems, and compared fuel loading among the seven fuel loading maps. Using each of the seven fuel loading maps as inputs, we compared fuel consumption and emissions for the two fuel consumption and emissions models.

To evaluate how model or data choice at each step in the modeling pathway potentially influences the final smoke emissions estimates, we developed two hypothetical pathways from fire size to smoke emissions. For one pathway, we always selected the highest values; that is, we chose the largest fire size from the available fire reporting systems, then selected the fuel loading map that predicted the highest quantities of biomass available to burn. Next, we selected the fuel consumption model with the highest predicted rates of consumption, and then applied the highest emissions rates produced by either FOFEM or Consume to the highest predicted fuel consumption quantities. We compared this "maximum outcome" pathway with a "minimum outcome" pathway, in which we selected the smallest fire size reported, then the smallest potential fuel loadings, and applied the lowest emissions rates to the lowest fuel consumption estimates.

RESULTS

Reported Fire Size

The NIFC system estimated the final fire size for the Tripod Fire Complex at 70 837 ha. This value was matched very closely by the ICS-209 reports (70 895 ha) and the MTBS system (71 307 ha). However, the MODIS fire detection system reported a final fire size of 99 045 ha, a 36 % difference from the NFIC estimate we used as our standard fire perimeter (Figure 2). The MODIS burned area product did not detect the Tripod Fire Complex because the Tripod burn area was characterized as snow or high aerosol.

Modeled Fuel Loading

Vegetation types were fairly similar across each fuel loading map investigated in this study (Figure 3). The general pattern of grasslands, shrublands, and open forests in the west-southwest portion of the burn area and denser conifer forests in the east and east-central portion of the burn area is consistent across the fuel loading maps studied. Fuel loading trends followed the vegetation type patterns, with
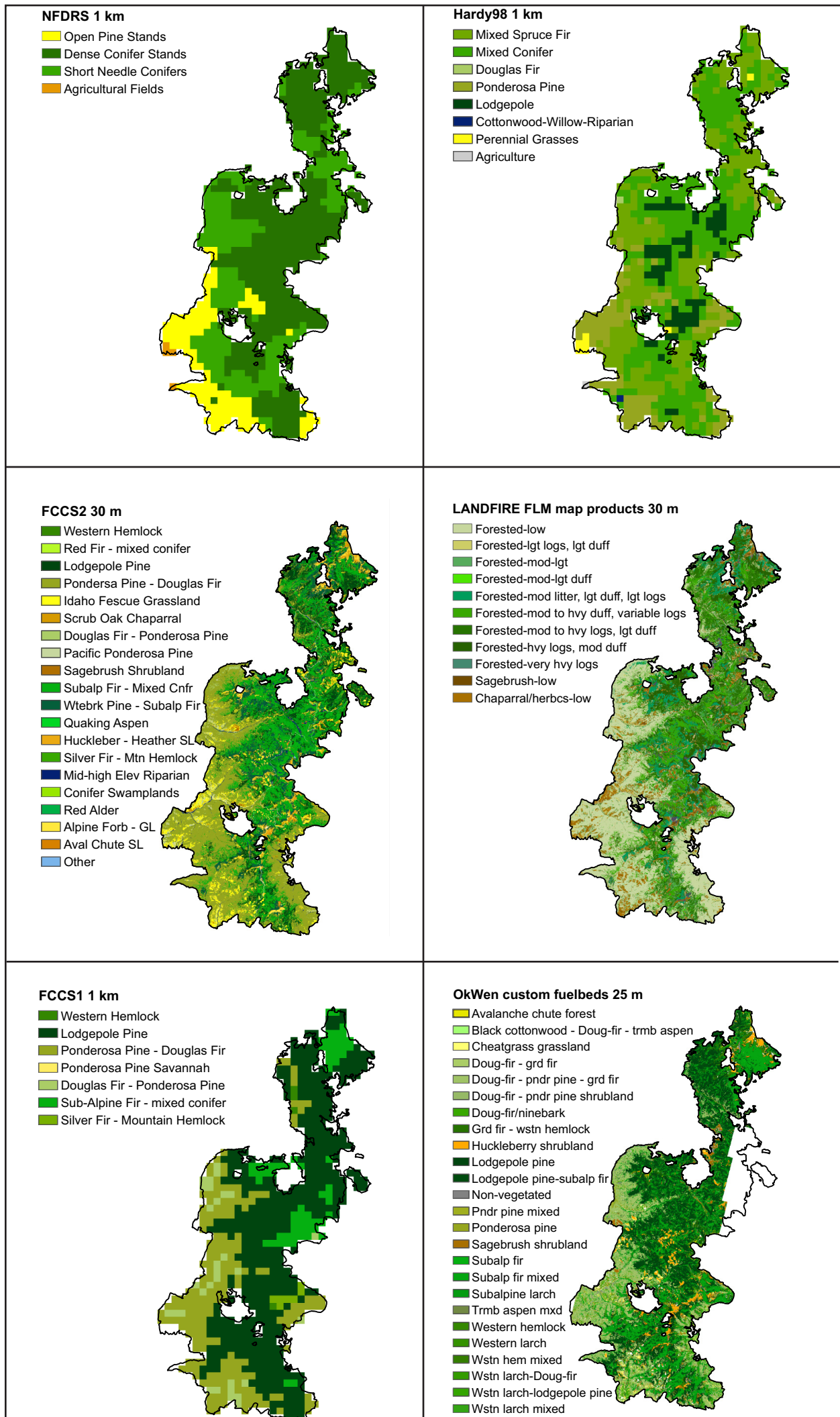
Figure 3. Spatial distribution of vegetation types burned during the Tripod Fire Complex. Burned area is defined using the NIFC fire perimeter. Grasslands, shrublands, and open pine stands are found in the eastern sections of the fire area, while dense, closed conifer stands are located in the central and eastern sections of the fire area. Note the finer scale vegetation classifications associated with the more recently produced maps (FCCS2, LANDFIRE FLM, OkWen custom fuelbeds).

lower fuel loadings to the west-southwest and higher fuel loadings in the east and east-central reaches of the Tripod Fire Complex burn area (Figure 4).

Across the seven fuel loading maps studied, total fuel loadings ranged from 2.7 million Mg to 8.8 million Mg (Table 3) for the area covered by the Tripod Fire Complex, a 108 % difference. Percentage difference is calculated as:
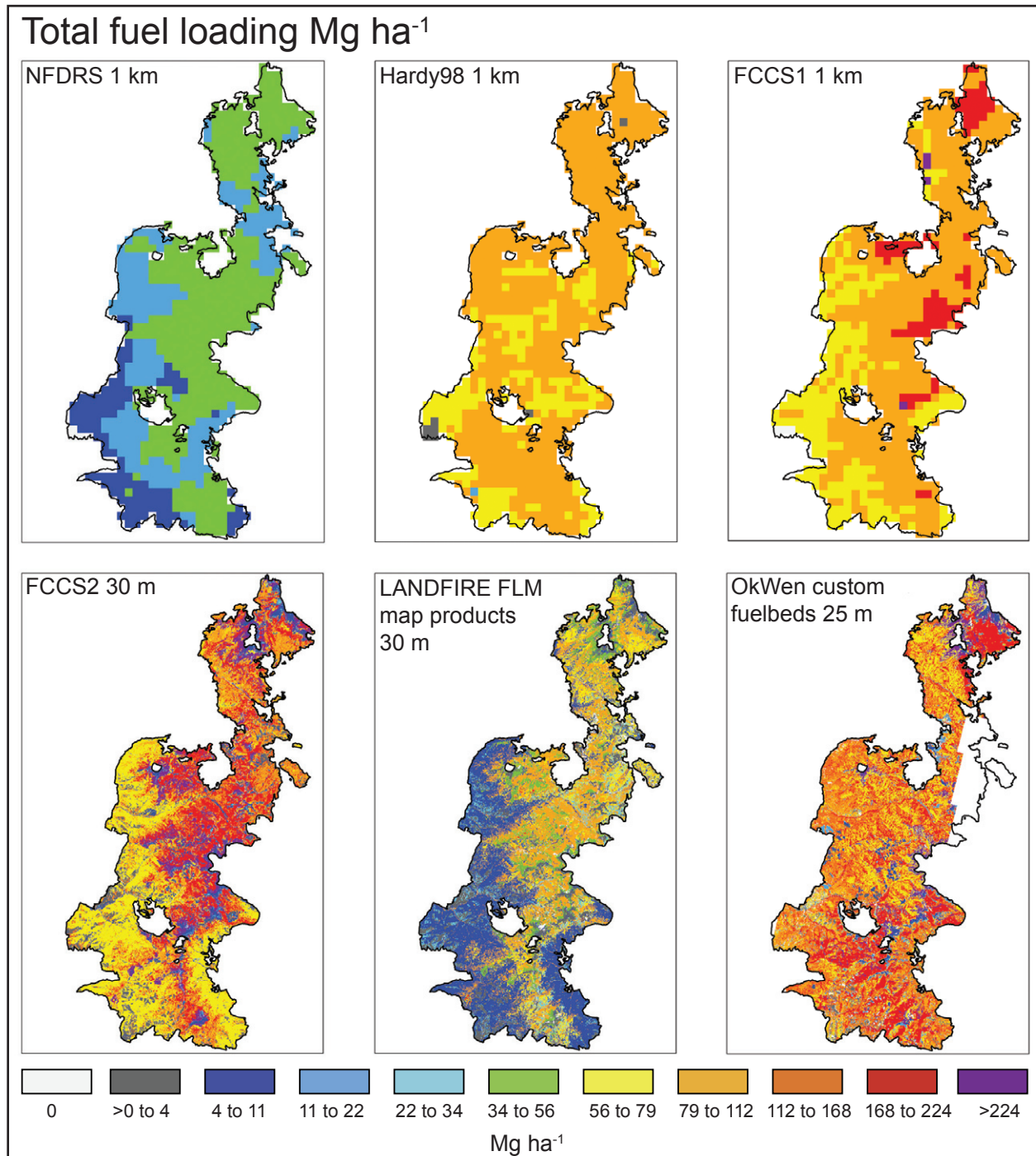

Figure 4. Total fuel loading maps for the Tripod Fire Complex. Burned area is defined by the NIFC fire perimeter.

Table 3. Fuel loading data for the Tripod Fire Complex based on seven different vegetation maps. Fuels are aggregated into ten categories: total fuels, canopy fuels, total surface fuels, shrub, grass, total woody, sound woody, rotten woody, litter, and duff.

	NFDRS (1 km)	Hardy98 (1 km)	FCCS1 (1 km)	FCCS2 (1 km)	FCCS2 (30 m)	LANDFIRE FLM (30 m)	Ok Wen (25 m)
Number of pixels	765	765	738	758	787 080	787 080	1 539 935
Hectares	70 483	70 483	71 100	71 350	70 837	70 837	64 994
Fuel loading							
Total (Mg)	2 718 590	4 931 377	6 315 591	8 792 675	7 875 389	3 017 456	8 367 184
Total (Mg ha^{-1})	38.6	69.9	88.8	123.3	111.2	42.6	128.7
Canopy (Mg)			1 367 157	2 496 356	2 224 207	505 622	2 565 159
Canopy (Mg ha^{-1})			19.3	35	31.4	7.2	39.5
Total surface (Mg)	2 718 590	4 931 377	4 948 433	6 296 319	5 651 181	2 511 835	5 802 024
Total surface (Mg ha^{-1})	38.6	69.9	69.5	88.3	79.8	35.4	89.2
Shrub (Mg ha^{-1})	1.1	1.1	0.2	0.9	0.9	0.7	1.6
Grass (Mg ha^{-1})	1.1	1.1	0.7	0.9	0.9	0.7	0.2
Total woody (Mg ha^{-1})	36.1	33.6	32.5	37.7	34.5	15.7	48.6
Sound woody (Mg ha^{-1})	36.1	33.6	25.6	22.6	20.8	9.9	36.3
Rotten woody (Mg ha^{-1})			6.9	14.8	13.7	5.8	12.1
Litter (Mg ha^{-1})			3.8	4.0	3.8	2.9	3.8
Duff (Mg ha^{-1})		34.1	31.4	43.3	38.6	15.5	34.7

$$\text{percentage difference} = 100 \times \left| \frac{m_1 - m_2}{\frac{1}{2}(m_1 + m_2)} \right| \quad (1)$$

The older generation of fuel loading maps (NFDRS, Hardy98, and FCCS1) predicted less fuel across the landscape than the more recent fine-scale fuel maps (FCCS2 and OkWen Custom Fuelbeds). Of interest, the fine-scale LANDFIRE FLM fuel map estimates of burnable fuel were consistently among the lowest for all fuel strata (Table 3). Total fuel loadings for the FCCS-based fuel loading maps (FCCS1, FCCS2, OkWen) were significantly higher than the NFDRS, Hardy98, and LANDFIRE FLM maps ($P < 0.003$). The FCCS-based fuel loading maps (FCCS1, FCCS2, Ok-Wen) were not significantly different from one another when intercompared.

Modeled Fuel Consumption

When we examined gross biomass consumption totals for the Tripod Fire Complex, the FOFEM model consistently estimated lower fuel consumption than the Consume model, as shown in Table 4 and Figure 5. Across all fuel loading maps evaluated (Table 4), Consume estimated total fuel consumption values ranging from 2 446 474 Mg (NFDRS 1 km) to 5 585 824 Mg (OkWen 25 m), while FOFEM estimated total fuel consumption values ranging from 1 796 054 Mg (LANDFIRE FLM 30 m) to 4 397 196 Mg (OkWen 25 m). When we directly compared FOFEM fuel consumption outputs with Consume fuel consumption outputs, FOFEM consistently produced fuel consumption estimates approximately 23 % (percentage difference calculated using Equation 1) lower than Consume across all seven sets of fuel loading inputs. For example, the FOFEM

Table 4. Fuel consumption data for the Tripod Fire Complex based on seven different vegetation maps. Fuels are aggregated into total fuels, canopy fuels, total surface fuels, shrub, grass, total woody, sound woody, rotten woody, litter, and duff.

|	NFDRS (1 km)		Hardy98 (1 km)		FCCS1 (1 km)		FCCS2 (1 km)		FCCS2 (30 m)		LANDFIRE FLM (30 m)		Ok Wen (25 m)	
Number of pixels	765.0		765.0		738.0		758.0		787 080.0		787 080.0		1 539 935.0	
Hectares	70 483.0		70 483.0		71 100.0		71 350.0		70 837.0		70 837.0		64 994.0	
Fuel loading (Mg)	2 718 590.0		4 931 377.0		6 315 591.0		8 792 675.0		7 875 389.0		3 017 456.0		8 367 184.0	
Fuel loading (Mg ha^{-1})	38.6		69.9		88.8		123.3		111.2		42.6		128.7	
Fuel consumption														
Fire effects model	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM
Total (Mg)	2 446 474	2 103 904	4 254 480	3 014 607	4 328 785	3 182 544	5 774 189	4 504 178	5 139 838	4 084 608	2 132 086	1 796 054	5 585 824	4 397 196
Total (Mg ha^{-1})	34.7	29.8	60.3	42.8	61.0	44.8	80.9	63.2	72.6	57.6	30.0	25.3	85.9	67.7
Canopy (Mg)	0.0	0.0	0.0	0.0	583 315	543 777	893 892	1 016 930	788 084	913 730	242 698	227 416	787 977	1 043 364
Canopy (Mg ha^{-1})	0.0	0.0	0.0	0.0	8.3	7.6	12.6	14.3	11.2	13.0	3.4	3.1	12.1	16.1
Total surface (Mg)	2 446 474	2 103 904	4 254 480	3 014 607	3 745 470	2 638 765	4 880 297	3 487 248	4 351 754	3 170 878	1 889 386	1 568 639	4 797 846	3 353 831
Total surface (Mg ha^{-1})	34.7	29.8	60.3	42.8	52.7	37.2	68.4	48.9	61.4	44.8	26.7	22.2	73.8	51.6
Shrub (Mg ha^{-1})	1.1	0.7	1.1	0.7	0.2	0.2	0.7	0.4	0.7	0.4	0.7	0.4	1.3	0.9
Grass (Mg ha^{-1})	1.1	1.1	1.1	1.1	0.7	0.7	0.7	0.9	0.9	0.9	0.7	0.7	0.2	0.2
Total woody (Mg ha^{-1})	32.5	27.8	29.6	27.3	28.0	20.2	32.1	26.5	29.1	24.4	14.6	12.1	40.6	32.7
Sound woody (Mg ha^{-1})	32.5	26.5	29.6	25.1	21.7	15.9	18.6	14.8	16.8	13.5	8.7	7.2	30.3	23.3
Rotten woody (Mg ha^{-1})	0.0	1.6	0.0	2.2	5.8	4.3	12.8	11.7	11.4	10.8	5.8	4.7	10.1	9.4
Litter (Mg ha^{-1})	0.0	0.0	0.0	0.0	2.2	3.8	2.5	4.0	2.2	3.8	3.6	2.9	2.7	3.8
Duff (Mg ha^{-1})	0.0	0.0	28.5	6.0	21.5	12.6	32.3	17.3	28.5	15.2	7.2	6.3	28.9	13.7
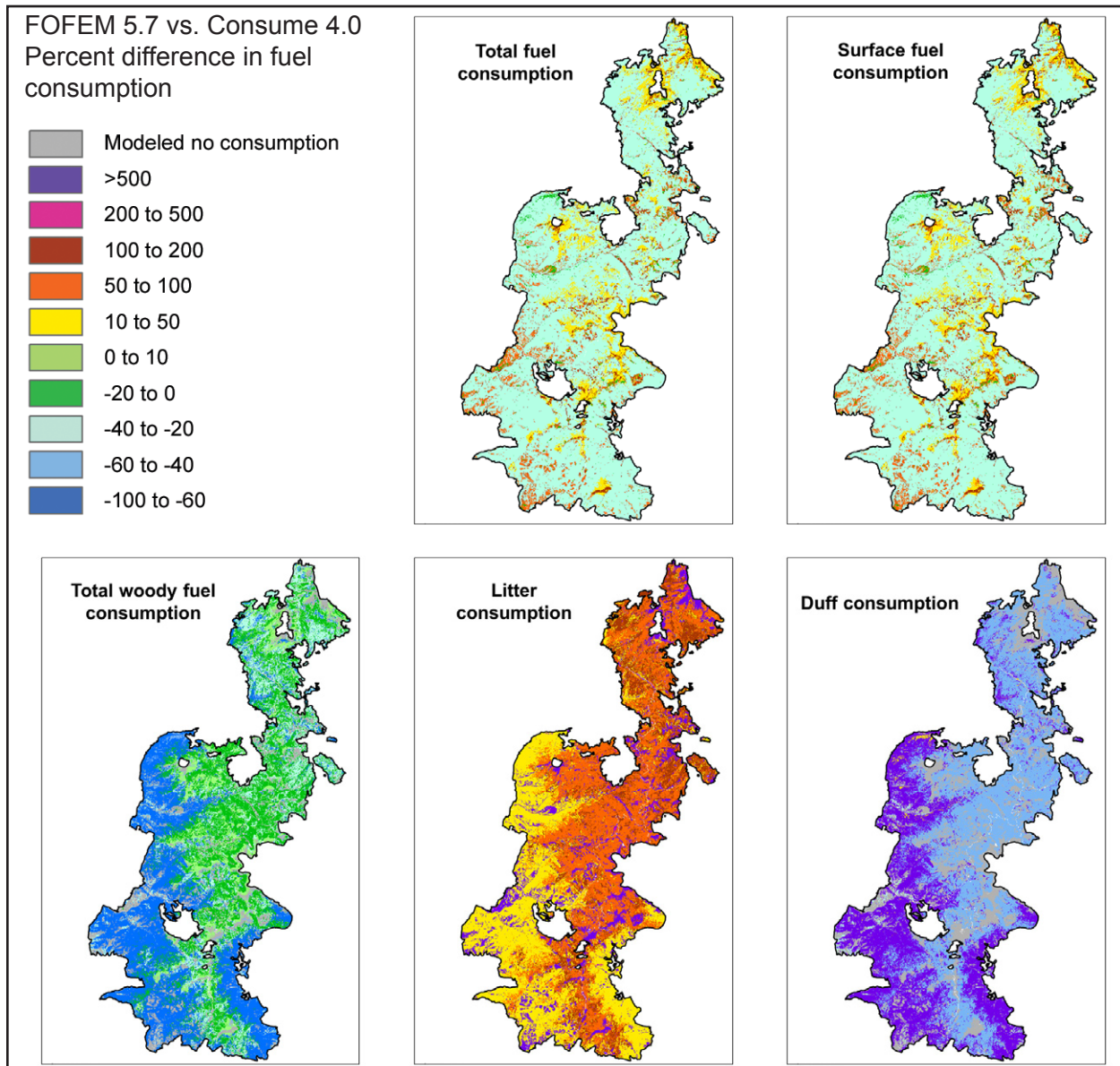
Figure 5. The percentage difference in fuel consumption between estimates from FOFEM 5.7 and Consume 4.0. The FCCS2 30 m map is used for modeling and display. Consume predicted higher consumption rates (negative differences) for total fuel and total surface fuel. Consume also produced higher consumption rates for total woody fuel in the western ranges of the fire. FOFEM produced higher duff consumption (positive differences) in the western ranges of the fire, while Consume predicted higher duff consumption in the east.

fuel consumption estimates for the OkWen fuel map (4 397 106 Mg) were 24 % lower than the Consume fuel consumption estimates (5 585 824 Mg) for the same fuel loading map.

Fuel consumption also varied by fuel type and fuel strata. For example, when estimating total downed woody fuel consumption, Con-sume estimated a higher rate of consumption in the more open forests, grasslands, and shrublands located in the west and southwest portion of the Tripod Fire Complex burn area compared to FOFEM (Figure 5). Consume-based woody fuel consumption rates were only slightly higher than FOFEM estimates in the

east-northeast sections of the burn area, characterized by conifer forests with deeper duff layers (Figure 5).

FOFEM estimated higher consumption rates for duff in the western regions of the fire area, while Consume-based duff consumption rates were higher than FOFEM-based rates in the eastern sections of the fire (Figure 5). For litter, FOFEM-based consumption rates were consistently higher than Consume-based rates across the Tripod Fire Complex burn area (Figure 5).

Modeled Smoke Emissions

Smoke emissions results followed an opposite pattern to fuel consumption, with FOFEM consistently estimating higher CO, CH_4, $PM_{2.5}$, and PM_{10} emissions than Consume (Table 5; Figure 6). For CO_2, Consume produced higher emissions estimates than FOFEM; however, this was not significant except for the Hardy98 fuel loading map ($P < 0.001$). The particulate ($PM_{2.5}$ and PM_{10}) emissions estimates showed greater variance by fuel type, as Consume estimated higher particulate emissions for the open lands in the west and southwest regions of the fire, while FOFEM estimated higher particulate emissions in the eastern reaches of the fire, which were dominated by closed conifer fuel types (Figure 6). Modeled emissions estimates for $PM_{2.5}$ were different only for the NFDRS *(P < 0.001)*, Hardy98 *(P < 0.001)*, and the OkWen custom FCCS fuel loadings cases ($P < 0.02$); PM_{10} emissions were different only when fuels inputs were provided by the NFDRS and Hardy98 fuel loading maps ($P < 0.001$).

Modeled Results vs. Observations

Field assessments of total woody fuel loading were consistently higher than modeled fuel loadings in all cases. Analysis using box and whisker plotting techniques revealed that the OkWen custom fuel loading map was the only map to provide fuel loading estimates within the range of the field observations, as shown in Figure 7. The median values and the central tendencies for all other modeled fuel loadings were far below the central tendencies for the field observations (Figure 7). Moreover, when we compared percentage differences, only the central tendency for the OkWen custom fuel model included zero (no difference to observations) within its range.

Observed fuel consumption rates prepared using the MTBS fuel severity maps, in combination with field-level observations of fuel consumption, were generally similar to the modeled fuel consumption within the Tripod Fire Complex burn area (Figure 8). Spatially, observed fuel consumption estimates were lower in the western and southern areas, which were dominated by more open forests, grasslands, and shrublands (Figure 8). Higher rates of fuel consumption were observed in the eastern reaches of the fire, where closed canopy conifer forests dominated the fuel type (Figure 8). FOFEM- and Consume-derived fuel consumption estimates followed a similar pattern and were generally within ±20 % of the MTBS-derived fuel consumption estimates (Figure 8). Overall, total fuel consumption estimated by FOFEM (56.8 Mg ha^{-1}) was slightly lower than the MTBS total of 59.7 Mg ha^{-1}, while total fuel consumption estimated by Consume (71.4 Mg ha^{-1}) was higher than the MTBS total. Comparisons of individual fuel types across the landscape indicated that Consume tended to estimate higher fuel consumption than MTBS for the closed conifer fuel types with more biomass available to burn, while Consume-based fuel consumption rates were generally lower than MTBS for the more open stand types. In contrast, FOFEM consumption rates were generally lower than MTBS-derived rates for most fuel types (Figure 8).

Modeling Pathways

Smoke emissions varied considerably when the maximum and minimum outcome modeling pathways were followed. The small-

Table 5. Smoke emissions data for the Tripod Fire Complex based on seven different vegetation maps.

|	NFDRS (1 km)		Hardy98 (1 km)		FCCS1 (1 km)		FCCS2 (1 km)		FCCS2 30m		LANDFIRE FLM (30 m)		Ok Wen (25 m)	
Number of pixels	765.0		765.0		738.0		758.0		787 080.0		787 080.0		1 539 935.0	
Hectares	70 483.0		70 483.0		71 100.0		71 350.0		70 837.0		70 837.0		64 994.0	
Fuel loading (Mg)	2 718 590.0		4 931 377.0		6 315 591.0		8 792 675.0		7 875 389.0		3 017 456.0		8 367 184.0	
Fuel loading (Mg ha^{-1})	38.6		69.9		88.8		123.3		111.2		42.6		128.7	
Fire effects model	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM
Fuel consumption (Mg)	2 446 474	2 103 904	4 254 480	3 014 607	4 328 785	3 182 544	5 774 189	4 504 178	5 139 838	4 084 608	2 132 086	1 796 054	5 585 824	4 397 196
Fuel consumption (Mg ha^{-1})	34.7	29.8	60.3	42.8	61.0	44.8	80.9	63.2	72.6	57.6	30.0	25.3	85.9	67.7
Emissions														
Fire effects model	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM
CH_4 (Mg ha^{-1})	0.1	0.2	0.2	0.6	0.2	0.4	0.3	0.6	0.3	0.5	0.1	0.2	0.3	0.6
CO_2 (Mg ha^{-1})	45.4	43.8	74.6	54.1	73.1	63.7	97.5	89.1	87.7	81.6	37.8	35.9	105.6	95.9
CO (Mg ha^{-1})	2.2	5.2	5.0	12.0	4.8	8.8	6.9	12.8	6.2	11.6	2.3	5.1	7.1	13.6
PM_{10} (Mg ha^{-1})	0.3	0.5	0.6	1.1	0.6	0.8	0.9	1.2	0.8	1.1	0.3	0.5	0.9	1.3
$PM_{2.5}$ (Mg ha^{-1})	0.3	0.4	0.5	0.9	0.5	0.7	0.7	1.0	0.6	0.9	0.2	0.4	0.7	1.1
PM (Mg ha^{-1})	0.5		0.9		0.9		1.2		1.1		0.4		1.3	
NMHC (Mg ha^{-1})	0.1		0.2		0.2		0.3		0.3		0.1		0.4	
NO_x (Mg ha^{-1})		0.04		0.00		0.04		0.10		0.10		0.02		0.10
SO_2 (Mg ha^{-1})		0.02		0.04		0.04		0.10		0.10		0.02		0.10
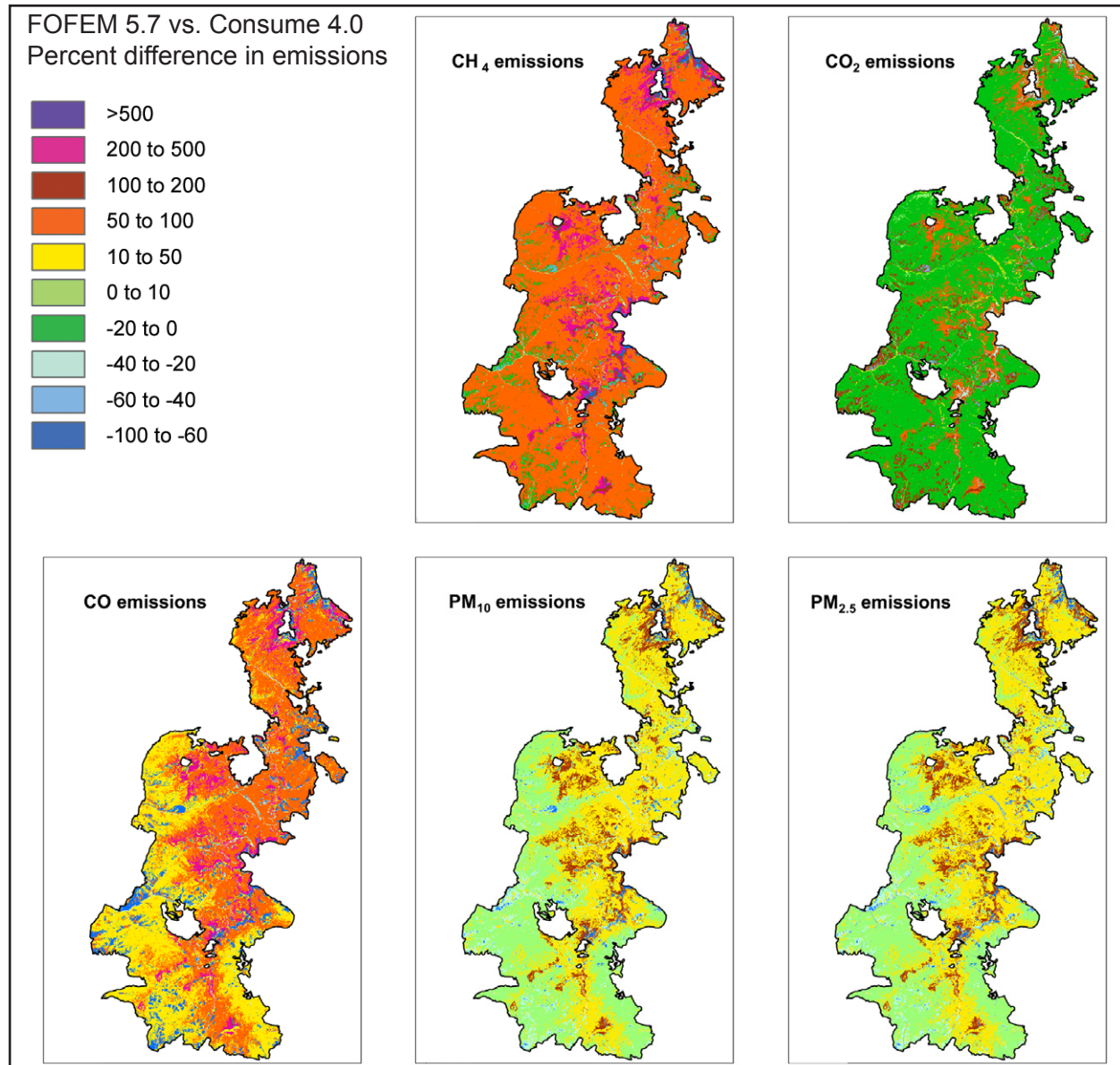
Figure 6. The percentage difference in emissions estimates from FOFEM 5.7 and Consume 4.0. The FCCS2 30 m map is used for modeling and display. FOFEM produced higher emissions (positive differences) for CH_4, CO, PM_{10}, and $PM_{2.5}$. Consume produced higher emissions for CO_2.

est fire size for this fire, reported by NIFC, was 70 837 ha. This is about 30 % lower than the largest fire size, reported by the MODIS fire detection product, of 99 045 ha, with an absolute difference of 28 208 ha. The non-detection by the MODIS burned area product was not considered in this analysis.

At the fuel loading step, modeled fuel loadings varied by a factor of 3 when compared across the NIFC fire perimeters. The NFDRS

fuel loading map reported a value of 38.6 Mg ha^{-1}, and the OkWen custom FCCS fuel loading map reported a value of 128.7 Mg ha^{-1} (Table 3). The maximum absolute difference in fuel loading was 90.1 Mg ha^{-1}.

Examining only consumption model differences, using the NIFC fire perimeter to estimate fire size and the FCCS2 as the reference fuel loading, FOFEM estimated 57.6 Mg ha^{-1} of consumption, while Consume's estimate
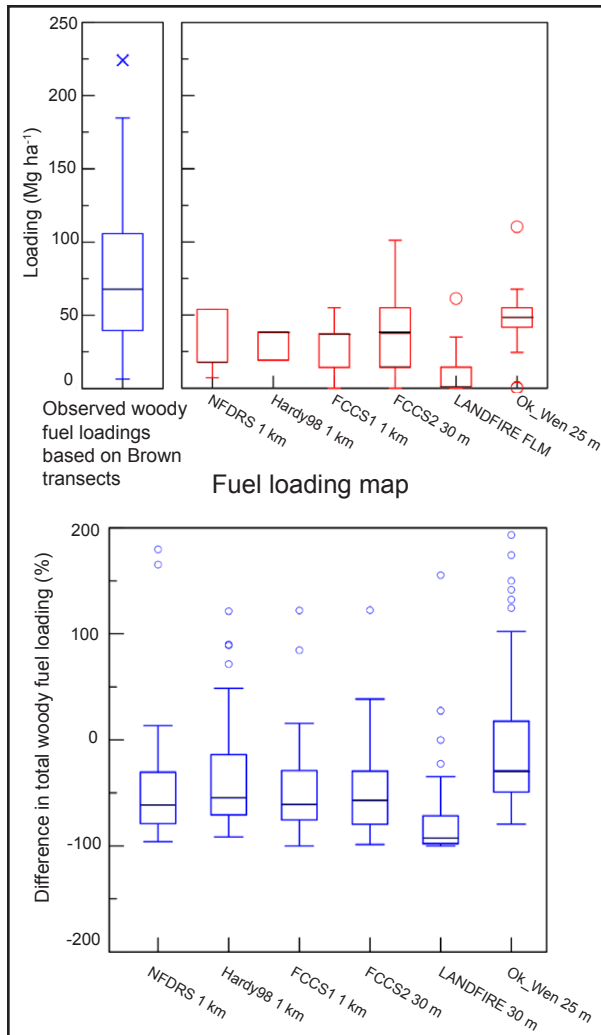
Figure 7. Box and whisker plots showing statistical comparisons of the woody fuel loading summaries from the CVS and the six fuel loading maps studied. Horizontal lines within the box indicate median values. Boxes encapsulate the central tendency (first and third quartile), and whiskers indicate values that lie within 1.5 times the interquartile ranges.

(72.6 Mg ha^{-1}) was 15.0 Mg ha^{-1} (or 26 %) higher (Table 4). When we compared fuel consumption for all fuel loading input options for FOFEM and Consume, fuel consumption varied from a low estimate of 25.3 Mg ha^{-1} (FOFEM and the LANDFIRE FLM fuel load-

ing map), to a high of 85.9 Mg ha^{-1} (Consume and the OkWen custom fuel loading map).

We intercompared smoke emissions using the NIFC fire perimeter estimate with FCCS2 as the reference fuel loading map. FOFEM estimated 0.91 Mg ha^{-1} of PM$_{2.5}$ emitted, while Consume estimated 0.63 Mg ha^{-1} of emitted PM$_{2.5}$ (Table 5; Figure 9). When we compared smoke emissions for all fuel loading input options for FOFEM and Consume, smoke emissions estimates for PM$_{2.5}$ varied from a low of 0.25 Mg ha^{-1} (Consume and the LANDFIRE FLM fuel loading map) to a high of 1.1 Mg ha^{-1} (FOFEM and the OkWen custom fuel loading map). The percentage difference values for all other emissions produced by FOFEM or Consume are shown in Figure 6.

The differences observed at each step clearly impacted subsequent steps in the modeling pathway. Using the high and low values at each step from fire size through PM$_{2.5}$ emissions, we found that the variances are compounded. For the "maximum outcome" pathway, a fire size of 99 045 ha (MODIS fire detection), a fuel loading of 12 322 606 Mg (Ok-Wen), and fuel consumption of 8 503 708 Mg (Consume) results in a total PM$_{2.5}$ emissions estimate of 106 574 Mg using FOFEM emissions (Table 6). In contrast, for the "minimum outcome" pathway, a fire size of 70 837 ha (NIFC), a fuel loading of 3 017 456 Mg (LANDFIRE FLM[1]), and a fuel consumption of 1 796 054 Mg (FOFEM) yields a total PM$_{2.5}$ emissions estimate of 17 467 Mg when Consume is applied (Table 6). These estimates differ by a factor of 6.

DISCUSSION

We noted clear differences at each step of the modeling pathway when estimating smoke emissions for the 2006 Tripod Fire Complex. Moreover, it was clear that differences ob-

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[1] Although NFDRS reported the lowest absolute fuel loadings, the LANDFIRE FLM pathway was used in this stage of the minimum possibilities pathway because the NFDRS did not include multiple fuel strata.
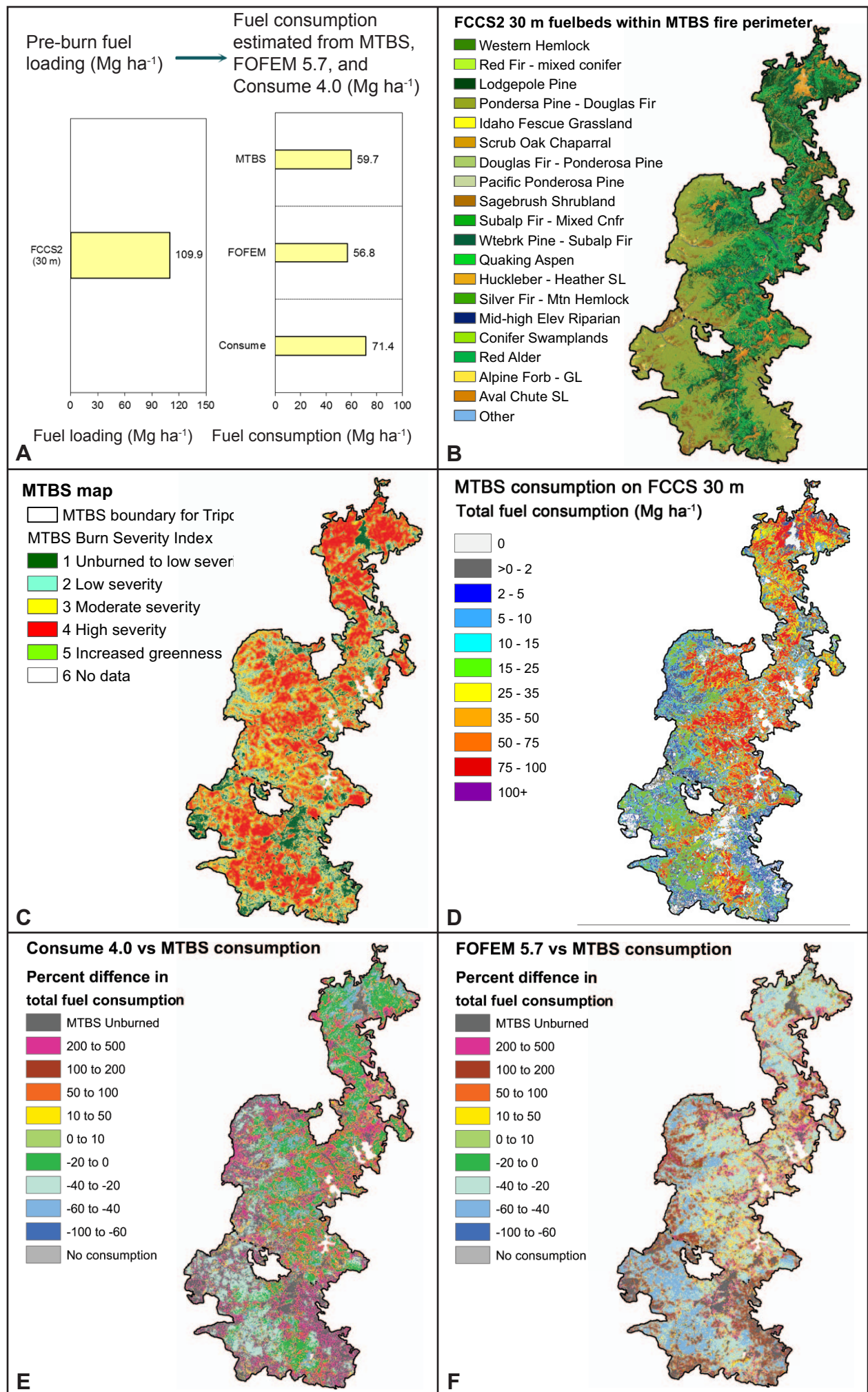
Figure 8. Fuel consumption estimated from MTBS linked to Composite Burn Index (CBI) and compared with Consume 4.0 and FOFEM 5.7 fuel consumption outputs. All results shown are based on the MTBS fire perimeter and FCCS2 30 m fuelbeds for the Tripod Fire Complex. This figure shows (A) the fuel loading and fuel consumption estimates from MTBS, FOFEM, and Consume; (B) the FCCS2 30 m vegetation map; (C) burn severity; and (D) the corresponding fuel consumption calculated from burn severity and CBI. Also shown in panels (E) and (F) are the differences (%) in fuel consumptions between MTBS and Consume (E) and MTBS and FOFEM (F).
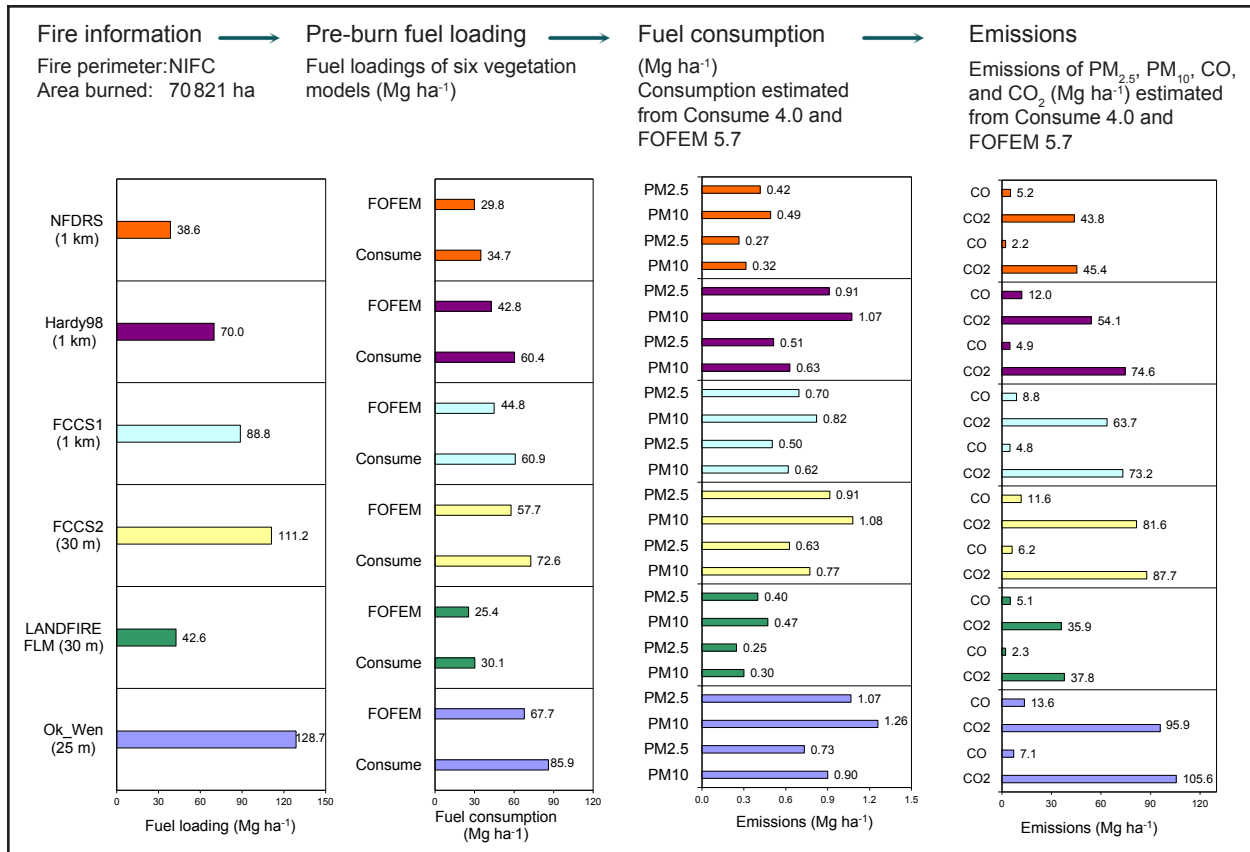
Figure 9. The outputs of the smoke emissions modeling pathway steps at a glance for the Tripod Fire Complex. Fire perimeter is from NIFC. Steps are as follows: fire information system, fuel loading, fuel consumption, and smoke emissions. The FCCS2 30 m fuel loadings are shown within the NIFC fire perimeter in Figure 8A. Using Consume 4.0 and FOFEM 5.7, we estimated fuel consumptions and emissions for $PM_{2.5}$, PM_{10}, CO, and CO_2.

served at one step were then propagated through the modeling process. Quantifying differences at various positions in smoke modeling pathways will provide information on areas in which improvements in the modeling process are needed.

Reported Fire Size

The differences observed here show that fire size information gathered from various fire detection systems may vary considerably. Selecting the optimal fire size and location information is easier for a single large fire, such as the Tripod Fire Complex, where good field-based observations were available and fire perimeters are maintained within publicly avail-

able databases such as GeoMac and MTBS. In the fire community, NIFC fire perimeters are considered the most accurate fire size information available (R. Harrod, personal communication). For smaller fires, precise fire perimeters may not be available.

At broad scales, fire detection systems that include multiple fires, such as the MODIS fire detection or burned area products, are commonly used (Knorr *et al.* 2012). Based on our results, the Tripod Fire Complex emissions would not be included in a large-scale emissions assessment if the MODIS burned area product were used as the fire area source of information (the Tripod Fire Complex burn area was characterized as snow or high aerosol; therefore, no fire was recorded in the system).

Table 6. Summary of the maximum and minimum values and associated differences at each step in the smoke emissions modeling pathway.

Fire size	Fuel loading	Fuel consumption	PM$_{2.5}$ emissions
99 045 hectares (maximum)	12 322 606 Mg (124.4 Mg ha^{-1})	8 503 708 Mg (85.9 Mg ha^{-1})	106 574 Mg (1.07 Mg ha^{-1})
70 837 hectares (minimum)	3 017 456 Mg (42.6 Mg ha^{-1})	1 796 054 Mg (25.4 Mg ha^{-1})	17 467 Mg (0.25 Mg ha^{-1})
Difference of 28 208 hectares	Difference of 9 305 150 Mg (81.8 Mg ha^{-1})	Difference of 6 707 654 Mg (60.5 Mg ha^{-1})	Difference of 89 107 Mg (0.82 Mg ha^{-1})
33 % difference	121 % difference	130 % difference	144 % difference
Best options for the Tripod Fire Complex			
MTBS 71 307 hectares	FCCS2 8 792 153 Mg (123.3 Mg ha^{-1})	FOFEM 4 506 602 Mg (63.2 Mg ha^{-1})	FOFEM 71 307 Mg (1.0 Mg ha^{-1})

Moreover, if the MODIS fire detection product were used to identify fire size and location, the emissions for the Tripod Fire Complex would be overestimated because fire size was overestimated by the fire detect product when compared with the NIFC fire perimeter data. Overestimating fire size using MODIS fire detection data is due, at least in part, to our assumption that each fire detect burned an entire pixel (Soja *et al.* 2006). Omitting fires or overestimating fire size will greatly influence the amount of fuel provided to the fuel consumption models, and under- or over-estimates of fuel consumption will directly lead to under- or over-estimating smoke emissions.

The MTBS system evaluated for this single fire case was in good agreement with the NIFC fire perimeter. This suggests that, at least for assessing large wildfires, MTBS would produce a result closer to reality as identified by fire managers. However, using MTBS does not address the problem of detecting small fires, which need to be greater than 404 ha in the western United States and greater than 202 ha in the eastern United States to be included in the MTBS database.

Modeled Fuel Loading

The large differences noted in fuel loading for the Tripod Fire Complex (Table 3; Figure 4) illustrate different approaches to mapping fuels across landscapes. The current generation of fuel loading maps (FCCS2, OkWen, LANDFIRE FLM; McKenzie *et al.* 2007, Lutes *et al.* 2009, French *et al.* 2011) has become increasingly comprehensive since the creation of the NFDRS as a tool for fire danger rating (Burgan *et al.* 1997*a*, Burgan *et al.* 1998). Much of the resulting variability in the mapped fuel loadings we observed was due to the omission of specific fuels strata such as canopy, shrubs, litter, or duff layers in the older fuel maps (NFDRS, Hardy98). Use of the current generation of fuel loading maps resolves these issues, as these fuels maps were specifically created to model fuel consumption and smoke emissions and now include canopy fuels and improved modeling of litter and duff.

The current fuel loading maps (bottom three panels in Figure 4) reflect our improved understanding of fuels in fire-prone landscapes, yet quantifying the natural variability in fuels across landscapes continues to be a problem (Ottmar *et al.* 2009, Keane and Reeves 2012). The significant variability in fuel loading we observed among the LANDFIRE FLM map and the two FCCS-based map products illustrates this issue. For this case, the approach used to produce the OkWen fuel loading map, for which local land managers interacted with

fire researchers to quantify fuel loadings across an extensive range of vegetation types and then mapped the fuels by vegetation type (McKenzie *et al.* 2007, Berg 2007), provided the best fit to the local condition. The OkWen custom FCCS fuel loadings largely agreed with the field data; this result was related, at least in part, to how the OkWen custom FCCS fuel loading map was produced.

Modeled Fuel Consumption

The good agreement among the modeled data and the MTBS satellite observations linked to the field observations of fuel consumption for the Tripod Fire Complex indicates that either FOFEM or Consume will provide acceptable estimates of fuel consumption for wildfires in the Pacific Northwest, provided that the fuels information supplied to the model characterizes the fuels appropriately. Smoke emissions modeling accuracy could be improved if fuel consumption algorithms were improved; however, much greater improvements to the estimates of smoke emissions could be gained by improving the estimates of the amount of fuel available to burn as the biggest differences, and largest uncertainties, were found among the estimates of fuel loading provided by the fuel loading maps and the field observations of fuel loading.

Modeled Smoke Emissions

The differences in modeled smoke emissions rates illustrate the importance of the selection of emission factors for smoke emissions modeling. FOFEM produced higher emissions for CO, CH_4, $PM_{2.5}$, and PM_{10}, while Consume produced higher CO_2 emissions. These results are due to different emission factors used in the FOFEM and Consume emissions calculations and the way each model handles the partitioning of fuel consumption into the flaming and smoldering phases. Further understanding of the emissions process,

and translation into an empirical description, will help to reduce these differences.

Modeling Pathways

This study demonstrates that the differences observed at one step of a modeling pathway are passed on to the subsequent steps of the pathway and influence the final results of modeling exercises, such as estimating smoke emissions. For the Tripod Fire Complex case study, the difference between maximum and minimum values at each modeling step was 33% for fire size, 121% for fuel loading, 130% for fuel consumption, and 144% for emissions estimation (for $PM_{2.5}$). The compounded differences between the maximum and minimum possible pathways demonstrate the importance of selecting the modeling pathway best suited for the fire location and region.

Best Options for the Tripod Fire Complex

As our results show, considerable uncertainty can be associated with modeling smoke emissions. This does not mean that we should abandon the modeling approach for estimating smoke emissions. Rather, our results show that, with some careful thought, managers can pick an appropriate option at each step in a smoke emissions modeling pathway. For example, the best option for estimating the area burned by the Tripod Fire Complex was the MTBS fire perimeter, which was easily accessible and spatially verified by the MTBS project team. Locally specific fuel loading maps such as the OkWen fuel loading map (custom FCCS fuelbeds) should be used when available, as this fuel loading map best matched the field observed fuel loadings available for this project. If custom, locally produced fuelbeds are not available, the standard FCCS fuelbeds (FCCS2) available from LANDFIRE (www.landfire.gov) should be used.

Our study results illustrate how FOFEM, when compared to Consume, provided fuel

consumption estimates that were closer to the fuel consumption estimates derived from the combined MTBS fire severity CBI field observations analysis; FOFEM therefore appears to be better than Consume for modeling both fuel consumption and smoke emissions on severe fires in this region. However, resource managers can and should perform retrospective analyses on historic fires in their region, such as we performed here, to determine which fuel consumption model performs best for the vegetation types that they are using to model smoke emissions at their local scale.

As noted throughout this paper, our best options for which models to use within a smoke modeling pathway are not the only options, and the results of a single case study should be used with caution; however, a smoke emissions pathway as outlined in this section will provide useful information needed to understand the tradeoffs between the ecological benefits of burning and the hazards due to the smoke emitted by burning.

CONCLUSIONS

Quantifying wildland fire emissions is a critical step in evaluating smoke impacts. Smoke emissions estimates require the use of modeling pathways that combine multiple sources of data and the linking of scientific models in a logical, progressive sequence. Fire emissions are typically modeled using information on fire size and location, coupled with fuel loading maps, which are then processed through consumption models capable of producing emissions estimates. In a complex modeling process, numerous options are available, and managers, scientists, and others who model fire emissions need to understand the uncertainties and differences in this process. Intercomparisons, such as the one conducted here, provide insights into the sensitivity of smoke emissions estimates to the variability present at each step in a modeling pathway. Use of accurate fire information and local fuels data is critical to reducing the amount of uncertainty in the overall modeling chain. The first step to providing better estimates of smoke emissions is to provide better estimates of the fuels available to burn. Under-or over-estimating fire size can lead to inaccurate representations of the amount of fuel available to burn, the amount of fuel consumed during a fire, and subsequently unrepresentative estimates of smoke emissions. Additional uncertainty when modeling smoke emissions can be introduced by the available fuel loading maps. For example, we found that all modeled fuel loading maps studied underestimated total woody fuel loading when directly compared with field-sampled fuel loading data. Locally produced fuel loading maps such as the OkWen custom FCCS fuel loading map can reduce some of the uncertainty due to fuel loading inaccuracies; however, our results suggest that fuel loading, and subsequent smoke emissions, are commonly underestimated on wildfire in the Pacific Northwest. Examination of other fires as part of SEMIP (N. Larkin, unpublished data) shows similar results, suggesting that the uncertainties identified here are important areas for future research and development.

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