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Abstract: Emissions from wildland fires are of interest for many reasons. Wildland fire smoke emissions are a potential human health hazard due to the production of fine-grained particulate matter (particles ≤ 2.5 microns in diameter, PM2.5), carbon monoxide (CO), and ozone (O3) 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 divergent scientific disciplines, and the linking of various scientific models in a logical, progressive sequence. Typically, estimations of fire size, available fuel loading (biomass available to burn), and the amount of 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 the 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 have significantly smaller variations (33% and 23%, respectively). The PM2.5 emission estimates from CONSUME and FOFEM vary by 37%. In addition, comparisons with available observational data demonstrate the value of utilizing local datasets where possible.

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Cover letter

Dear Editors

Please consider the attached manuscript titled “Comparing fire size, fuels, fuel consumption, and smoke emissions estimates: A case study using the 2006 Tripod wildfire” for publication in Ecological Modelling.

We feel that Ecological Modelling will be a good avenue to present the modeling comparisons we conducted here as our study provides insights into the smoke emissions modeling process. The information provided here will be useful to land managers and modelers tasked with estimating emissions from wildfires and prescribed fires.

Sincerely

Stacy A Drury

Sonoma Technology, Inc.

***Highlights (for review)**

Title: Comparing fire size, fuels, fuel consumption, and smoke emissions estimates: A case study using the 2006 Tripod wildfire.

Highlights:

- We compared the data inputs (modeled and observed) and data outputs at each step in a smoke emissions modeling pathway (fire detection - fuel characterization - fuel consumption – smoke emissions) to improve the process of estimating emissions from wildfires.
- Differences were observed at each step in the modeling pathway.
- Differences at one step in the modeling pathway were passed down to the subsequent steps.
- Fire detection data (fire size and location) and fuel loading data (biomass quantification) were the most variable.
- Fuel consumption estimates from the fuel consumption models FOFEM and Consume were the least variable.

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Abstract

Emissions from wildland fires are of interest for many reasons. Wildland fire smoke emissions are a potential human health hazard due to the production of fine-grained particulate matter (particles ≤ 2.5 microns in diameter, $PM_{2.5}$), 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 divergent scientific disciplines, and the linking of various scientific models in a logical, progressive sequence. Typically, estimations of fire size, available fuel loading (biomass available to burn), and the amount of 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 the 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%,[1] while fire size and fuel consumption have significantly smaller variations (33% and 23%, respectively). The $PM_{2.5}$ emission estimates from CONSUME and FOFEM vary by 37%. In addition, comparisons with available observational data demonstrate the value of utilizing local datasets where possible.

1.0: Introduction

Smoke emissions from severe wildfires 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, $PM_{2.5}$), carbon monoxide (CO), and ozone (O_3) precursors (Hardy et al., 2001; Koichi et al., 2010; Larkin et al., 2009; Ottmar et al., 2009; Reinhardt and Ottmar, 2004). Such fires also impact human welfare by contributing to regional haze and reduced visibility. Smoke impacts on health and visibility are a growing concern due to the multiple 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 (Ferry et al., 1995; Mutch, 1994; Westerling et al., 2006).

To address smoke impacts on public health and welfare, 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 accurate, reasonable estimates of smoke emitted by biomass burning during both wildfire and prescribed fire events (French et al., 2011; Knorr et al., 2012; Larkin et al., 2009; Ottmar et al., 2009). 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.

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[1] Percent difference calculated as $|(m_1 - m_2)/((m_1 + m_2)/2)|$.

To help guide land managers through the complicated process of modeling smoke emissions, decision support frameworks have been developed to provide modeling pathways that guide users through the required steps of (1) identifying fire size and location; (2) determining fuel loadings; (3) estimating fuel consumption; (4) producing realistic estimates of smoke emissions (see 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). Often a variety of datasets and models are available within such a framework for performing each step in the modeling pathway (Goodrick et al., 2012; Larkin et al., 2009), and the selection of datasets and models can have a significant impact on the resulting estimates of smoke emissions (Larkin et al., 2012).

1.1: SEMIP Overview

The Smoke and Emissions Model Intercomparison Project (SEMIP) (Larkin et al., 2012; http://www.airfire.org/projects/semip) was designed to create an open standard for comparing smoke and emissions models against each other and against real-world observations, thereby providing quantitative information that can be translated into user-accessible guidance as to which models perform best under various circumstances. 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, U.S.A. (Larkin et al., 2012). In this case study, we intercompare five fire reporting systems, seven fuel loading maps, and two fuel consumption models; when combined into a modeling pathway, these models 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 the 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 discussed here provides a single large fire case study and illustrates how the variability at each modeling step can be quantified for individual fires.

1.2: The Tripod Fire Complex

Two separate lightning strikes occurring on July 3, 2006, and July 24, 2006, triggered the Spur Peak Fire and the Tripod Fire in Washington State's Okanogan-Wenatchee National Forest. These fires burned together as the Tripod Fire Complex, one of the largest wildfire events in Washington State history. The Tripod Fire Complex (Figure 2) burned across a range of vegetation types, including grasslands, sage shrublands, Douglas-fir (*Psuedotsuga menziesii*) forests, Ponderosa Pine (*Pinus ponderosa*) forests, Lodgepole Pine (*Pinus contorta*) forests, and mixed-species forests from July until November. Fire severity 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 (Goodman, 2006; Prichard et al., 2010).

The size of the Tripod Fire Complex ensured that the event would be captured by numerous fire reporting systems, which enabled comparisons of reported fire location and size information. In addition, fuels and fuel loadings were 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. In addition, post-burn field observations of fuel consumption were available for comparison with modeled estimates. The availability of these data sources, which are discussed in more detail below, made the Tripod Fire Complex attractive for fire, fuel loading, consumption, and emissions analyses.

1.3: Smoke Emissions Modeling Literature

Three recent papers provide interesting insights into the potential for different outcomes when using models to generate smoke emissions. Ottmar et al. (2009) reviews the current knowledge, data, and the types of predictive models commonly used for smoke emissions modeling. Knorr et al. (2012) discusses issues surrounding smoke emissions modeling on a global scale. French et al. (2011) discusses 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: identifying fire location and size, quantifying the fuels available to burn, estimating how much of that fuel is consumed, and, ultimately, quantifying the amount and type of pollutants emitted. 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. Large differences were also observed in the fire detection and fire size estimates in these studies (Knorr et al., 2012; Ottmar et al., 2009). 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, carbon emissions from wildfires were found to vary regionally. The 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. 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. 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 pathway(s) must be evaluated further. The goal of this study was to use the 2006 Tripod Fire Complex in the Pacific Northwest as a case study by quantifying the differences in smoke emissions produced using various datasets and models at each step in the modeling pathway. Section 2 details the methods, models and datasets used. Section 3 presents the results, separated into fire size, fuel loadings, consumption, and emissions. Section 4 discusses these results and their implications for both model and dataset development and land management use. Section 5 summarizes the work presented here.

2.0: Methods and Technical Approach

We focus here on quantifying the impact of selecting various datasets and models for estimating fire size, fuel loading, fuel consumption, and emissions, as these were the most readily quantifiable steps in smoke emissions modeling pathways. The specific datasets and models compared for each of these steps are described below.

2.1: Fire Size Information

A number of systems are currently in use by fire management personnel to identify wildfire size and location. For this analysis, we evaluated fire size information from the five fire reporting systems outlined below:

- *ICS-209 incident reports* – The ICS-209 report is the official form used to report fire size information for large incidents.[2] These reports provide a set of coordinates indicating the fire ignition point, and the spatial extent of the fire must be incorporated from other sources. In absence of other spatial information, a circle with an area that approximates the reported fire size can be drawn from the fire origin point (Figure 3). This approach is problematic, as a fire rarely expands in all directions equally.
- *Monitoring Trends in Burn Severity (MTBS) maps* – The primary objective of the MTBS project is to provide spatially explicit burn severity information for national analysis of fire severity trends (Eidenshink et al., 2007). MTBS maps are produced using the differenced normalized burn ratio (dNBR) approach, where pre- and post-wildfire Landsat imagery is used to identify areas where the landscape burned during wildfires (Eidenshink et al., 2007).[3]
- *NIFC/GeoMac* – The National Interagency Fire Center (NIFC) keeps polygon records of fire perimeters constructed by geographic information system (GIS) specialists assigned to the incident. The final perimeter is recorded by a GIS specialist "tracing" the outline of the fire by walking the perimeter or using a helicopter as a GIS platform. 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, personal communications).
- *Moderate Resolution Imaging Spectroradiometer (MODIS) Burn Detect* – MODIS uses the Terra (AM) and Aqua (PM) satellite passes to provide products on fire location, energy emitted, flaming and smoldering ratios, and estimated area (number of pixels) burning. In the burn detect product, MODIS uses a contextual algorithm to detect fires using the strong footprint in mid-infrared radiation that is characteristic of ongoing wildland fires (Giglio et al., 2003). Fire area was determined by aggregating all pixels detected by the MODIS burn detect product as burning by the Tripod Fire Complex (July to November 2006) into a single raster file.

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[2] ICS-209 reports can be accessed at ftp://ftp.nifc.gov/ or http://fam.nwcg.gov/fam-web/hist_209/report_list_209.

[3] The MTBS fire extent maps are available at http://www.mtbs.gov.

- *Moderate Resolution Imaging Spectroradiometer (MODIS) Burn Area* – The Burn Area MODIS product uses the land surface reflectance data from the Terra (AM) and Aqua (PM) satellite passes to determine the day of burning for each 500 m^2 pixel. The burn area product is produced on a monthly basis and provides the approximate day of burning for each pixel within a given month. Fire size is estimated by combining all pixels that burned during a particular set of days (Boschetti et al., 2009).

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

2.2: 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. Table 1 shows the various fuel strata available for each.

- *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, 1997; 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 (Table 1). Woody fuels are further classified into moisture classes by diameter: 1-hr woody fuels are 0-0.635 cm in diameter, 10-hr fuels are 0.635 - 2.54 cm in diameter, 100-hr fuels are 2.54 - 7.62 cm in diameter, and 1000-hr fuels are > 7.62 cm in diameter (Anderson, 1982). NFDRS maps do not include information on larger woody fuels, decomposed (rotten) woody fuels, canopy fuels, litter, or duff.
- *Hardy 1998* – 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 eighteen broad categories created using an EROS Data Center LAND Characterization Class product. The fuel loadings by vegetation cover type are presented for live shrubs; live herbaceous fuels; 1-, 10-, 100-, 1000-, and 10,000 + hour downed woody fuels; litter; and duff (Table 1). In this classification, 1000-hr fuels are 7.62 to 22.86 cm in diameter, 10,000-hr fuels are 22.86 to 50.80 cm in diameter, and 10,000 plus-hr woody fuels are > 50.80 cm in diameter.
- *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 were 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 (1, 10, 100, 1000, and 10,000+ hour), shrubs, herbs, grasses, canopy fuels, dead standing trees (snags), stumps, litter, moss, lichens, and duff (Table 1).

- *Fuel Characteristic Classification System – LANDFIRE Crosswalk maps (FCCS2 30m & 1km)* – We refer to the FCCS-LANDFIRE crosswalk maps as FCCS2 in order to distinguish them from the original FCCS maps described above. The FCCS2 at 30m map provides standard FCCS fuelbeds and associated fuel loadings mapped at 30m for the continental United States, Alaska, and Hawaii. The FCCS2 map at 30m uses the LANDFIRE map product structure and is available as a LANDFIRE map product. To produce this map, the standard FCCS fuelbeds and the LANDFIRE Existing Vegetation Types (EVT) map layer were crosswalked (D. McKenzie personal communication). Then, 199 standard FCCS fuelbeds were assigned to individual map pixels by linking FCCS2 fuelbeds to EVT coded pixels. FCCS2 at 1 km provides a scaled version of the fuelbed information displayed at 30 m in the LANDFIRE system. FCCS2 at 1 km was derived for the continental United States using the FCCS2 at 30 m fuel loading map (D. McKenzie personal communication).
- *Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) Fuel Loading Models (FLM)* – The LANDFIRE FLM map product provides fuel loading values for surface fuels at 30 m resolution across the continental United States (J. Herynk personal communication). The FLMs were produced from 4,046 field plots where shrubs, herbs, downed woody fuel, litter and duff were measured and classified into fuel loading models based on expected emissions (Lutes, 2009; Sikkink et al., 2009). Each fuel loading model was mapped by linking fuel loadings to vegetation type using LANDFIRE map products (J. Herynk personal communication). Fuel loading values represented in the FLM fuel loadings map include duff, litter, and 1-, 10-, 100-, and 1000-hour downed woody fuels (Table 1).
- *Okanogan-Wenatchee National Forest FCCS Custom Fuelbeds map (OkWen custom FCCS)* – The OkWen fuelbed map consists of a set of 83 custom 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).

Plots of vegetation types were prepared for each fuel loading map. Additional plots were created for each fuel strata (canopy, shrubs, herbaceous, woody fuels, duff, and litter), and composite plots were created for total fuel loading and total surface fuel loading. Summary fuel loading statistics (min, 1st quartile, median, 3rd quaritile, max) in Mg per hectare were calculated for each fuel map, and relative differences (with FCCS 2 set as the reference map) were calculated to identify potential variability across the landscape by data source.

2.3: Fuel Consumption

Fuel consumption modeling systems estimate fuel consumption on a stand of trees level (Reinhardt and Dickinson, 2010). Spatial assessments of fuel consumption during a single large wildfire event can be estimated using the fuel loading maps discussed above. In addition to total fuel consumption, a time profile estimate of fuel consumption by phase (flaming, smoldering, and residual) is also considered because the quantity and mixture of emissions varies by phase.

The First Order Fire Effects Model (FOFEM) 5.7 and Consume 4.0 were applied to the Tripod Fire Complex. FOFEM and Consume contain fuel consumption algorithms that estimate fuel consumption based on fuel loading (fuel available to burn) and fuel condition (moisture of fuels, fuel state); additional details on these systems are provided below.

- *FOFEM 5.7* – FOFEM provides estimates of fuel consumption for canopy, shrubs, herbaceous fuels, downed woody fuels (1-, 10-, 100-, 1000+ hour fuels), duff, and litter. FOFEM uses the Burnup model to predict consumption of woody fuels. Consumption of other fuels is predicted using empirical equations or rule-of-thumb algorithms (Reinhardt and Dickinson, 2010; Reinhardt et al., 1997).
- *Consume 4.0* – Consume predicts fuel consumption for each of the following fuels/vegetation strata: canopy, shrubs, herbaceous, downed woody fuels (1-, 10-, 100-, 1000-, 10,000+ hour fuels), litter, moss, lichen, and duff. Consume calculates consumption for duff, litter, and woody fuels using empirically derived algorithms. Default (i.e., rule-of-thumb) equations are used to predict canopy, shrub, and herbaceous fuel consumption. Consume 4.0 is the Python recoding of Consume 3.0 completed by the Michigan Technical Research Institute.

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, fuel moisture inputs to the models were developed using the Wildland Fire Assessment System (WFAS; Burgan et al., 1997) and the Fire Emissions Prediction Simulator (FEPS; Anderson et al., 2004). Fuel moisture for fuel consumption modeling is measured as percent moisture content by fuel category determined gravimetrically (wet weight – dry weight/dry weight). During the fire season, WFAS produces and maps daily estimates of 10-, 100-, 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, a FEPS fuel moisture lookup table (Table 2) was used to determine duff and 10-hr fuel moisture values that correspond to a 1000-hr fuel moisture value of 8%. The duff and 10-hr values were set to 25% and 6%, respectively.

A canopy consumption value of 60% was applied in both FOFEM and Consume; this is a rule of thumb assumption used for estimating canopy consumption in a wildfire. Also, Consume requires a percent area blackened value to determine shrub biomass consumed, and because the fire burned severely, we set the area blackened value to 95%. Once all input data and model settings were prepared, Consume and FOFEM were run on each of the seven fuel loading maps to identify variability in fuel consumption resulting from model choice.

To evaluate this variability, fuel consumption plots were created from FOFEM and Consume outputs for each fuel loading map, including difference plots by fuel loading map. Also, summary statistics (min, 1st quartile, median, 3rd quaritile, max) in Mg per hectare were calculated for each fuel loading map.

2.4: 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. This includes 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).

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 3; Hao, 2003; Ward et al., 1993). 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 FOFEM (Albini and Reinhardt, 1995). In this process, Burnup calculates heat intensity. Flaming ignition is assumed to occur at heat intensities > 15 kW/m^2, and smoldering ignition occurs below 15 kW/m^2 (FOFEM 5.7 Help document).

Consume 4.0 provides several alternative emission factors for modeling smoke emissions (Prichard et al., 2005). For the fuels burned during the Tripod Fire Complex, emissions were estimated using the Consume default emission factors (Table 4), as these are settings commonly used for modeling fuels across landscapes. The Consume default emissions factors are averages of all emissions factors in Consume for natural fuels and are assigned by fuel type (Douglas-fir, mixed conifer, ponderosa pine, hardwood, juniper, sage brush) and consumption phase (flaming, smoldering, residual smoldering (Prichard et al., 2005). 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., 2005).

Smoke emissions were compared 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. Smoke emissions were also compared across fuel loading inputs to identify potential influences of fuel loadings on later steps in the smoke emissions modeling pathway. Comparisons were performed for the five pollutants common to both FOFEM and Consume: CO, CO_2 CH_4, $PM_{2.5}$ and PM_{10}.

2.5: Observational Data

Observational plot data from the late 1990s sampled by the Pacific Northwest Current Vegetation Survey (CVS; Johnson, 2001) were obtained from the Okanogan-Wenatchee National Forest (E. Peterson, Personal Communication). These data were sampled following the protocol outlined in Johnson (2001) by the CVS inventory team using standard tree and fuels inventory techniques (Johnson, 2001). Woody fuels data from the CVS project were processed to provide direct observations for comparisons with modeled fuel loading data from each fuel loading map. For each plot located within the Tripod Fire Complex area, the woody fuel data were summarized into size classes (10-hr, 100-hr, 1000-hr and total woody fuels) and the biomass available to burn was calculated following Brown (1974). Intercomparisons between the modeled and observed woody fuel loadings were statistically assessed using box and whisker analysis (Systat 13 Users guide).

To evaluate modeled fuel consumption estimates in the Tripod Fire Complex, MTBS satellite observations of burn severity were linked to field estimates of fuel consumption to provide observed fuel consumption estimates (Justice et al., 2010). The MTBS burn severity maps include gridded estimates of burn severity (unburned, low, moderate, high). When coupled with composite burn inventories (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 (Justice et al., 2010). For the Tripod Fire Complex, CBI methodology was coupled with post-fire field sampling of vegetation and fuels data to produce indices relating fuel consumption to MTBS burn severity (Justice et al., 2010). The resulting fuel consumption indices link field observations of fuel consumed to MTBS burn severity classes. In our study, we utilized 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 Area for comparison with modeled estimates.

2.6: Modeling Pathways

To evaluate potential differences in smoke emissions due to alternative fire information data, fuel and consumption models, or alternative smoke emissions computation, analyses were completed on model output at each level in the modeling pathway (see also Figure 1):

Fire Size → Fuel Loading Map → Fuel Consumption → Smoke Emissions

The output from each step in the modeling pathway was intercompared. Fire size was compared for each of five fire reporting systems. Fuel loading was compared among the seven fuel loading maps. Fuel consumption and emissions were compared for the two fuel consumption and emissions models using each of the seven fuel loading maps as inputs.

To fully evaluate each alternative for the entire pathway with the options present at each step in this study, 70 scenarios (5 fire sizes x 7 fuel loading maps x 2 fuel consumption/emissions modeling systems) would be required. We limited the number of scenarios evaluated by identifying the maximum and minimum parameter at each step. These values were used to analyze the differences in smoke emissions output by selecting either the maximum or minimum values at each modeling step. For example, a hypothetical pathway was developed in which the largest fire size from the available fire reporting systems was chosen, followed by selection of the fuel loading map that predicted the highest quantities of biomass available to burn. Next, the fuel consumption model with the highest predicted rates of consumption was selected, and then we applied the highest emissions rates produced by either FOFEM or Consume to the highest predicted fuel consumption quantities. This “maximum outcome” pathway was compared with a “minimum outcome” pathway, in which the smallest fire size reported was selected, then the smallest potential fuel loadings, and the lowest emissions rates were applied to the lowest fuel consumption estimates.

2.7: Significance Testing

Due to the large number of sample points in the fuel loading, fuel consumption, and smoke emissions data sets (>1 million values for one fuel loading map), the model results were aggregated proportionately by vegetation type and statistically evaluated for differences in total fuel loadings, total fuel consumption, and total pollutant emissions for CO, CO_2 CH_4, $PM_{2.5}$ and PM_{10}. The aggregated data sets reproduced the trends in the data while allowing us to compute multiple comparison tests using the Tamhane's T2 Test for significance (alpha = 0.05), used when variances are unequal. Tamhane's T2 test is a conservative post-hoc comparison test that can be used in place of standard ANOVA tests for data with unequal variances (Systat v 13 users guide).

3.0: Summary of Results

This section presents the results of comparisons between datasets, models, and modeling pathways, as well as discussion of the sensitivity of smoke emission estimates to the range of choices available for each step in the overall pathway.

3.1: Reported Fire Size

The final fire size for the Tripod Fire Complex was estimated at 70,837 hectares by the NIFC system, and this value was matched very closely by the ICS-209 reports (70,895 hectares) and the MTBS system (71,307 hectares). However, the MODIS burn detect system reported a final fire size of 99,045 hectares, a 33% difference (see Figure 3). The MODIS burn area product did not detect the Tripod Fire Complex, as the Tripod burn area was characterized as snow or high aerosol (Figure 3). The non-detect of the Tripod Fire Complex by the MODIS burn area product and the much higher estimate of fire size by the MODIS burn detect when compared with the field-based NIFC fire perimeter show the large potential for under- or overestimating fire size when satellite data is used exclusively.

3.2: Modeled Fuel Loading

Vegetation types were fairly similar across each fuel loading map investigated in this study (Figure 4). The older 1-km resolution fuel maps (NFDRS, Hardy98, FCCS1) classify vegetation into broad classes such as open pine stands and ponderosa pine stands, while the later fine-scale map products (FCCS2 and OkWen Custom FCCS) break the fuel types into more specific designations (Figure 4). However, 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 lower fuel loadings to the west-southwest and higher fuel loadings in the east east-central reaches of the Tripod burn area (Table 5; Figures 5 and 6).

Total biomass loadings ranged from 2.7 million Mg to 8.4 million Mg (Table 6) for the area covered by the Tripod Fire Complex. In general, the older generation of fuel loading maps (NFDRS, Hardy98, FCCS1) predicted less fuel across the landscape than the later fine-scale fuel maps (FCCS2, 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 6). In fact, when total fuel loading estimates for the Tripod Fire Complex area were compared statistically using Tamhane's T2 test, LANDFIRE FLM fuel loadings were significantly lower than all fuel loading maps except NFDRS (significant p values = < 0.0005; $p > 0.9995$ for the NFDRS comparison). In addition, total fuel loadings for the more recent FCCS-based fuel loading maps were significantly different from the NFDRS, Hardy98, and LANDFIRE maps (p values < 0.003). However, when the FCCS-based fuel loadings were intercompared, differences between the maps were generally not significant, though the FCCS2 1-km map did differ significantly from the FCCS1 1-km map ($p = 0.013$).

Relative differences in fuel loading were pronounced among the seven fuel loading maps studied (Figure 6). The FCCS2 1-km map was arbitrarily set as the standard, as it was the most comprehensive national-scale map. In comparisons with FCCS2, the NFDRS, Hardy98, and FCCS1 fuel loading maps all modeled lower fuel loadings across the Tripod Fire landscape. For the fine-scale 30-m maps, comparisons among FCCS2 30, LANDFIRE FLM, and the OkWen Custom FCCS indicated that LANDFIRE FLM modeled less fuel across the landscape than FCCS2, while the OkWen Custom FCCS fuel loading map modeled higher fuel quantities across the same landscape (Figure 6).

3.3: Modeled Fuel Consumption

When gross biomass consumption totals were examined for the Tripod Fire Complex, the FOFEM model consistently estimated lower fuel consumption than the Consume model, as shown in Table 6, Table 7, and Figure 7. Across all fuel loading maps evaluated, Consume estimated total fuel consumption values ranging from 2,446,474 Mg (NFDRS 1-km) to 5,585,824 Mg (Ok-Wen 25-m), while FOFEM estimated total fuel consumption values ranging from 1,796,054 Mg (LANDFIRE 30-m) to 4,397,196 Mg (Ok-Wen 25-m). However, these fuel consumption differences were not significant when the Tamhane T2 test was applied, despite Consume predicting significantly (p value < 0.0005) more fuel consumption than FOFEM when Hardy98 fuel loadings were used as input.

Fuel consumption also varied by fuel type and fuel strata. For example, when estimating total downed woody fuel consumption, Consume estimated a higher rate of consumption in the more open forests, grasslands, and shrublands located in the west and southwest portion of the Tripod Burn area compared to FOFEM (Figure 4 and Figure 8). 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 8).

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 8). For litter, FOFEM-based consumption rates were consistently higher than Consume-based rates across the Tripod Burn area (Figure 8).

3.4: 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 6; Figure 9). For CO_2, Consume produced higher emission estimates than FOFEM; however, this was not significant except for the Hardy98 fuel loading map ($p < 0.0005$). The particulate ($PM_{2.5}$ and PM_{10}) emissions estimates showed greater variance by fuel type, as Consume estimated higher particulate emissions for the more 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 more closed conifer fuel types (Figure 9). Modeled emissions estimates for $PM_{2.5}$ were significantly different only for the NFDRS ($p < 0.0005$), Hardy98 ($p < 0.0005$), and the OKWen Custom FCCS fuel loadings cases ($p < 0.02$), and PM_{10}

emissions were significantly different only when fuels inputs were provided by the NFDRS and Hardy98 fuel loading maps (p values < 0.0005).

3.5: Modeled Results vs. Observations

Field assessments of total woody fuel loading were consistently higher than modeled fuel loadings in all cases. Based on a box-and-whisker analysis, the OKWen custom fuel loading map was the only map that provided fuel loading estimates in the range of the field observations, as shown in Figure 10. The central tendencies for all other modeled fuel loadings were far below the central tendencies for the field observations. Moreover, when percent differences were compared, only the central tendency for the OKWen custom fuel model included zero (no difference to observations) within its range. For this case, the approach used to produce the OKWen Fuel loading map, which consisted of quantifying fuel loadings across an extensive range of vegetation types and then mapping the fuels by vegetation type (Berg, 2007; McKenzie et al., 2007), provided the best fit to the local condition.

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 (Figures 7 and 11). Spatially, observed fuel consumption estimates were lower in the western and southern areas, which were dominated by more open forests, grasslands, and shrublands (Figure 11c). Higher rates of fuel consumption were observed in the eastern reaches of the fire where closed conifer forests dominated the fuel type (Figure 11c). FOFEM- and Consume-derived fuel consumption estimates followed a similar pattern and were generally within ± 20 percent of the MTBS-derived fuel consumption estimates (Figure 11). Overall, total fuel consumption estimated by FOFEM (56.7 Mg/ha) was slightly lower than the MTBS total of 59.6 Mg/ha, while total fuel consumption estimated by Consume (71.3 Mg/ha) was higher than the MTBS total. Comparisons of individual fuel types across the landscape (Figure 11e and f) 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 11f).

3.6 Modeling Pathways

Smoke emissions varied considerably when the maximum and minimum outcome modeling pathways were followed. The smallest fire size reported for this fire was by NIFC of 70,837 hectares which was about 30% lower than the largest fire size reported for this fire was by the MODIS Burn Detect (99,045 hectares), with an absolute difference of 28,208 hectares. The non-detect by the MODIS burn 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, and the OkWen custom FCCS fuel loading map reported a value of 128.7 Mg/ha (Table 6). The absolute difference in fuel loading was 90.1 Mg/ha (see section 3.2 for more details).

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 of consumption, while Consume's estimate (72.6 Mg/ha) was 15.0 Mg/ha (or 26%) higher (Table 6; Section 3.3). When fuel consumption was compared for all fuel loading input options for FOFEM and Consume, fuel consumption varied from a low estimate of 25.3 Mg/ha (FOFEM and the LANDFIRE FLM fuel loading map), to a high of 85.9 Mg/ha (Consume and the OkWen custom fuel loading map).

Smoke emissions were intercompared, using the NIFC fire perimeter estimate and with FCCS2 as the reference fuel loading map , FOFEM estimated 0.91 Mg/ha of $PM_{2.5}$ emitted, while Consume estimated 0.63 Mg/ha of emitted $PM_{2.5}$ (Table 6; Figure 12; Section 3.4). When smoke emissions were compared for all fuel loading input options for FOFEM and Consume, smoke emission estimates for $PM_{2.5}$ varied from a low of 0.25 Mg/ha (Consume and the LANDFIRE FLM fuel loading map) to a high of 1.1 Mg/ha (FOFEM and the OkWen custom fuel loading map). The values for all other emissions produced by FOFEM or Consume are shown in Figure 4.

The differences observed at each step were clearly passed through the modeling pathway from one step to the subsequent step. Taking the high and low values at each step from fire size through to $PM_{2.5}$ emissions, we find the variances are compounded. For the "maximum outcome" pathway, a fire size of 99,045 hectares (MODIS Burn Detect), a fuel loading of 12,322,606 Mg (OkWen), 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 8). In contrast, for the "minimum outcome" pathway, a fire size of 70,837 hectares (NIFC), a fuel loading of 3,017,456 Mg (LANDFIRE FLM[4]), 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 8). These estimated differ by a factor of 6.

4.0: 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 observed at one step were passed down to later steps during the modeling process. Quantifying differences at various positions in smoke modeling pathways will provide information on areas where improvements in the modeling process are needed.

4.1: Reported Fire Size

There is a large potential for errors to be passed on to subsequent steps in a smoke emissions modeling pathway. 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, which had good field-based observations and the NIFC fire perimeters available. 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.

[4] Although NFDRS had the lowest absolute fuel loadings, the LANDFIRE FLM pathway was used in this stage of the minimum possibilities pathway, as the NFDRS did not include multiple fuel strata.

On larger scales, fire detection systems that include multiple fires such as the MODIS burn detect or burn 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 burn area product was used as the fire area source of information (the Tripod burn area was characterized as snow or high aerosol; therefore, no fire was recorded in the system). Moreover, if the MODIS burn detect product was used to identify fire size and location, the emissions for the Tripod Fire Complex would be overestimated because fire size was overestimated by the burn detect product when compared with the NIFC fire perimeter data. Omitting fires or overestimating fire size will greatly influence the amount of fuel provided to the fuel consumption models, and under- or overestimates of fuel consumption will directly lead into under- or overestimation of the 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, more study is needed, as this is a single fire case. Also, using MTBS does not address the problem with detecting small fires, as fires need to be > 404 ha (1,000 acres) in the western US and > 202 ha (500 acres) in the eastern US to be included in the MTBS database.

4.2: Modeled Fuel Loading

The large differences noted in fuel loading for the Tripod Fire Complex (Table 6; Figure 5) illustrate different approaches to mapping fuels across landscapes . The current generation of fuel loading maps (French et al., 2011; Lutes, 2009; McKenzie et al., 2007) have become increasingly more comprehensive since the creation of the NFDRS as a tool for fire danger rating (Burgan, 1997; Burgan et al., 1998). Much of the resulting variability in the mapped fuel loadings was due to the omission of specific fuels strata such as canopy, shrubs, litter, or duff layers by the fuel-map. Use of the current generation fuel loading maps resolves these issues, and more recently developed maps 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 (Keane and Reeves, 2012; Ottmar et al., 2009). The significant variability in fuel loading we observed among the LANDFIRE FLM map and the two FCCS based map products illustrate this issue. The OkWen Custom FCCS fuel loadings largely agreed with the field data, and this result was related, at least in part, to how the OKWen Custom FCCS fuel loading map was produced. The OkWen map is a local map, produced for a specific area based on site specific inputs such as stand type, stand age, and stand development. This production of the OkWen map was carried out by local land managers and fire researchers with specific knowledge of the local fuels (McKenzie et al., 2007).

4.3: 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 on wildfires in the Pacific Northwest, provided that the fuels information supplied to the model characterizes the fuels appropriately. Model accuracy could be improved if fuel consumption algorithms were improved; however, much greater improvements at this time could be gained by improving the estimates of the amount of fuel available to burn.

4.4: Modeled Smoke Emissions

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

4.5: Modeling Pathways

The results of this study demonstrate that the differences observed at one step of a modeling pathway are passed on to the subsequent steps of the pathway. It is clear that the choices made at each step 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 that is suited best for the fire location and region.

5.0: Conclusions

Quantifying wildland fire emissions is a critical step for evaluations of the impact of smoke. 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.

We used the 2006 Tripod Fire Complex to assess sources of variability in smoke emissions modeling. Our findings indicate the data and models selected at each step of the modeling pathway significantly affect smoke emissions estimates. The largest variations were observed at fire size and fuel loading steps, while fuel consumption estimates showed the least variation.

For the single fire case, modeled smoke emissions will better represent reality if direct observational data such as the NIFC fire perimeter is used to accurately determine the fire size and location. In addition, the agreement between the observed fuel loadings and the OkWen fuel loading map suggests that fuel loading maps produced on local scales using locally collected data result in more accurate assessments of fuels on the local landscape.

Consumption and emissions calculations were the most similar parts of the modeling chain. This is not entirely unexpected as the two models used here, FOFEM 5.7 and Consume 4.0, were produced in the Pacific Northwest and were developed and tested on vegetation similar to the Tripod Fire Complex (Prichard et al., 2005; Reinhardt et al., 1997). When comparing FOFEM and Consume across regions, French et al. 2011 found that the two models produced similar results for a fire in the Pacific Northwest but produced dissimilar results in other parts of the US. This finding suggests that our conclusion may only apply to the Pacific Northwest and further intercomparisons are needed outside this region.

In summary, examination of the Tripod Fire Complex shows that emissions calculations can be highly uncertain. Use of accurate fire information and local fuels data are critical in reducing the amount of uncertainty in the overall modeling chain. Examination of other fires done as part of the same Smoke and Emissions Model Intercomparison Project (Larkin et al., 2012) show similar results, suggesting that the uncertainties identified here are important areas for future research and development.

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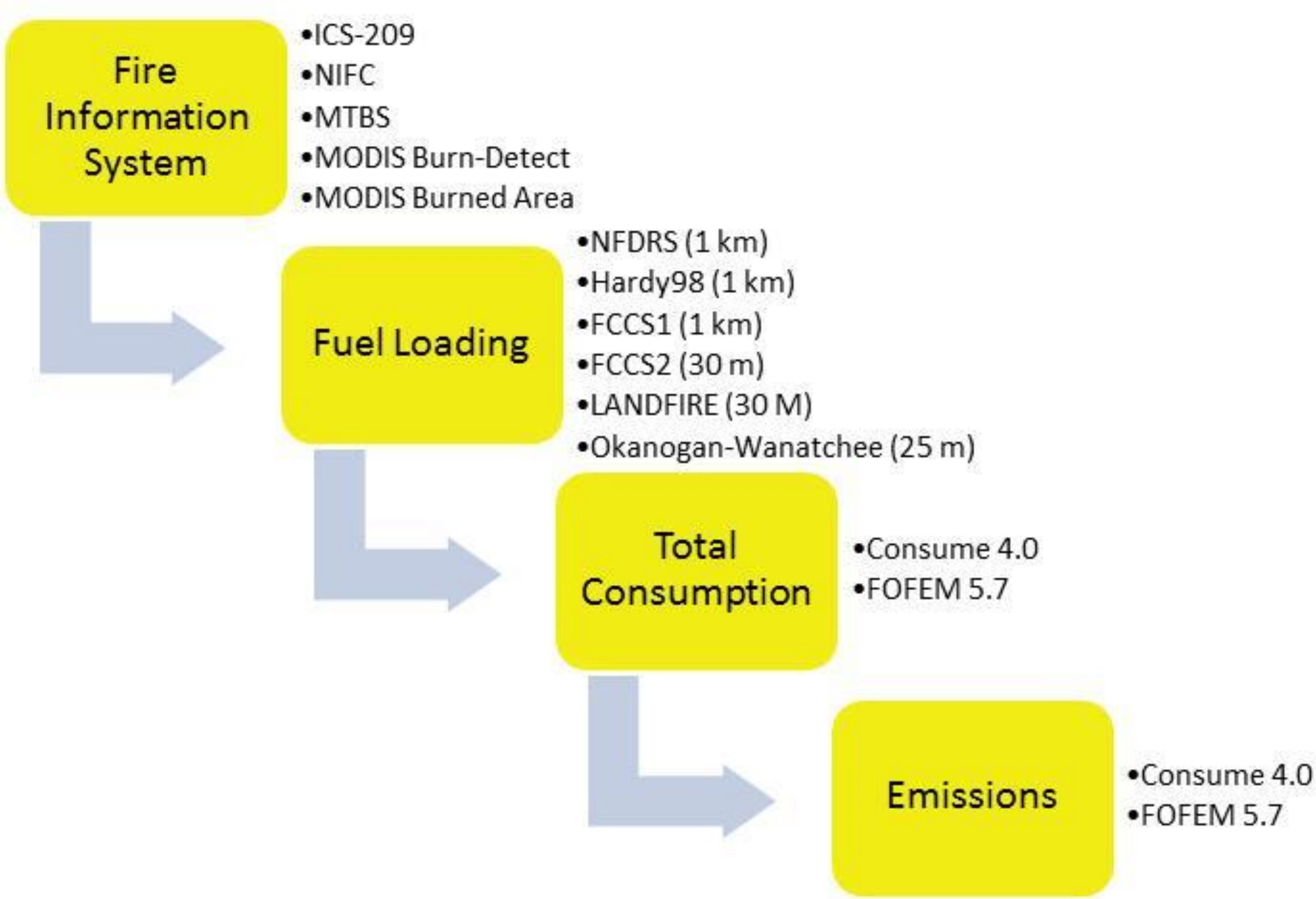
Figure 1



Fire Information System
•ICS-209
•NIFC
•MTBS
•MODIS Burn-Detect
•MODIS Burned Area
Fuel Loading
•NFDRS (1 km)
•Hardy98 (1 km)
•FCCS1 (1 km)
•FCCS2 (30 m)
•LANDFIRE (30 M)
•Okanogan-Wanatchee (25 m)
Total Consumption
•Consume 4.0
•FOFEM 5.7
Emissions
•Consume 4.0
•FOFEM 5.7

Figure 2

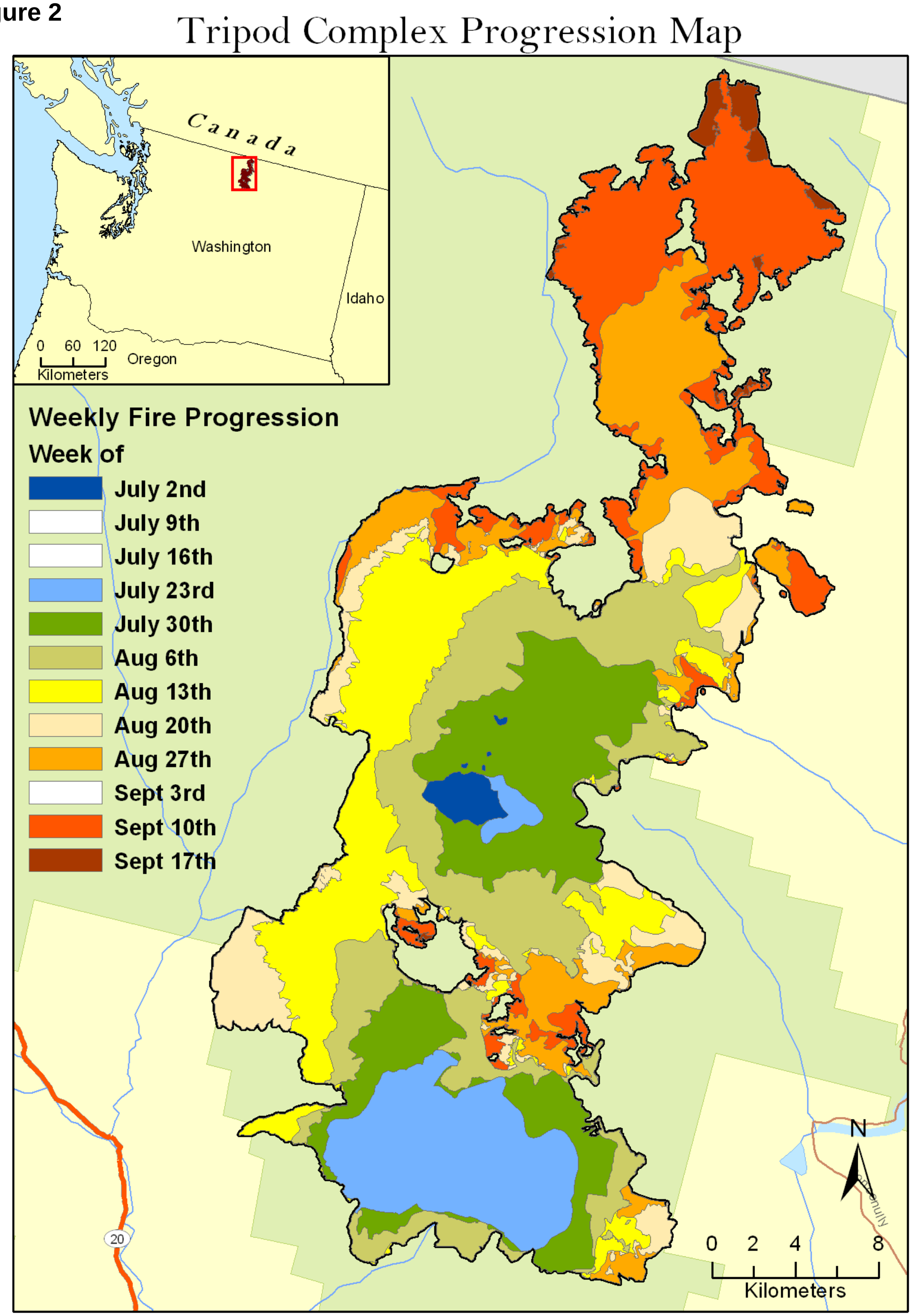
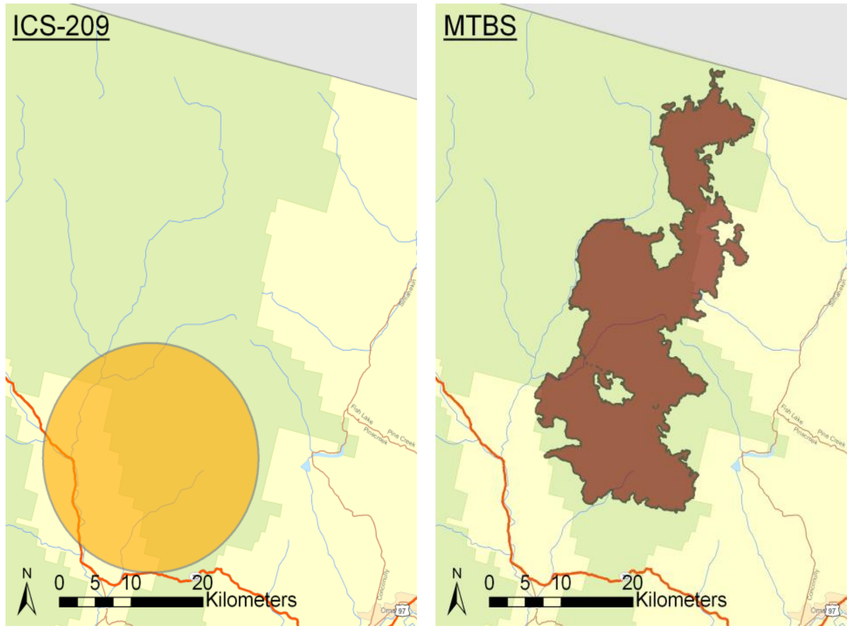

Tripod Complex Progression Map
Canada
Washington
Idaho
Oregon
0 60 120
Kilometers
Weekly Fire Progression
Week of
July 2nd
July 9th
July 16th
July 23rd
July 30th
Aug 6th
Aug 13th
Aug 20th
Aug 27th
Sept 3rd
Sept 10th
Sept 17th
20
N
0 2 4 8
Kilometers

Figure 3

Fire Reporting System	Area Burned Hectares (US Acres)
ICS-209	70,895 (175,184)
MTBS	71,307 (176,203)
NIFC	70,837 (175,042)
MODIS Burn-Detect	99,045 (244,745)
MODIS Burned Area	N/A



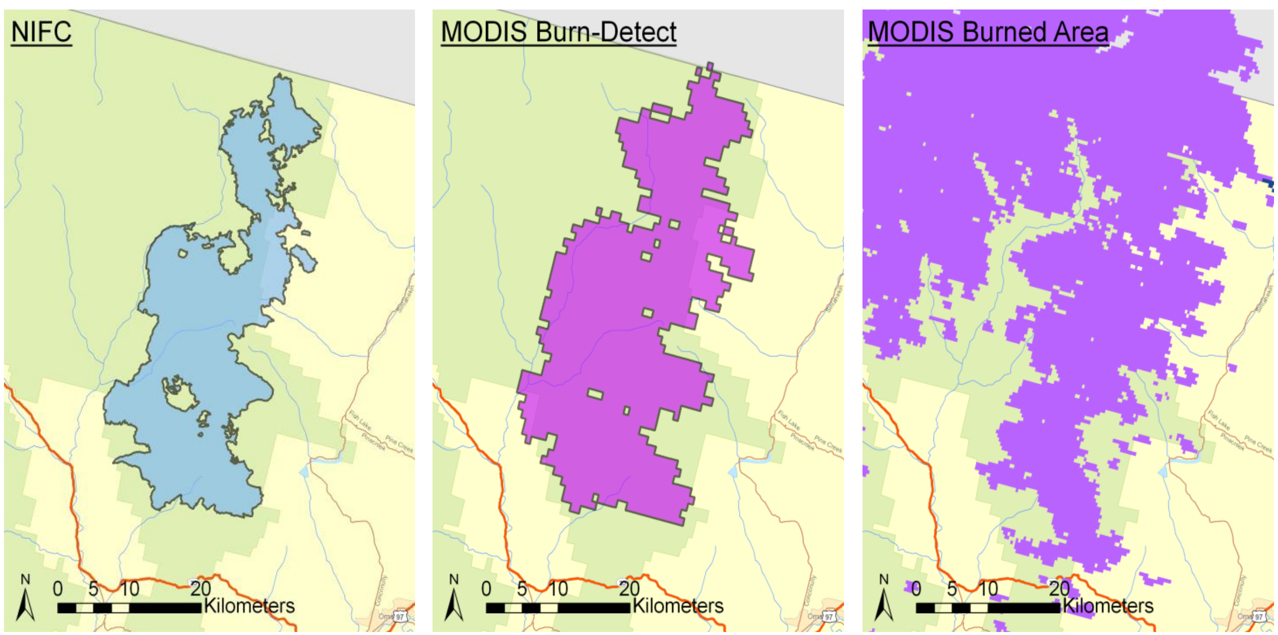


Figure 4

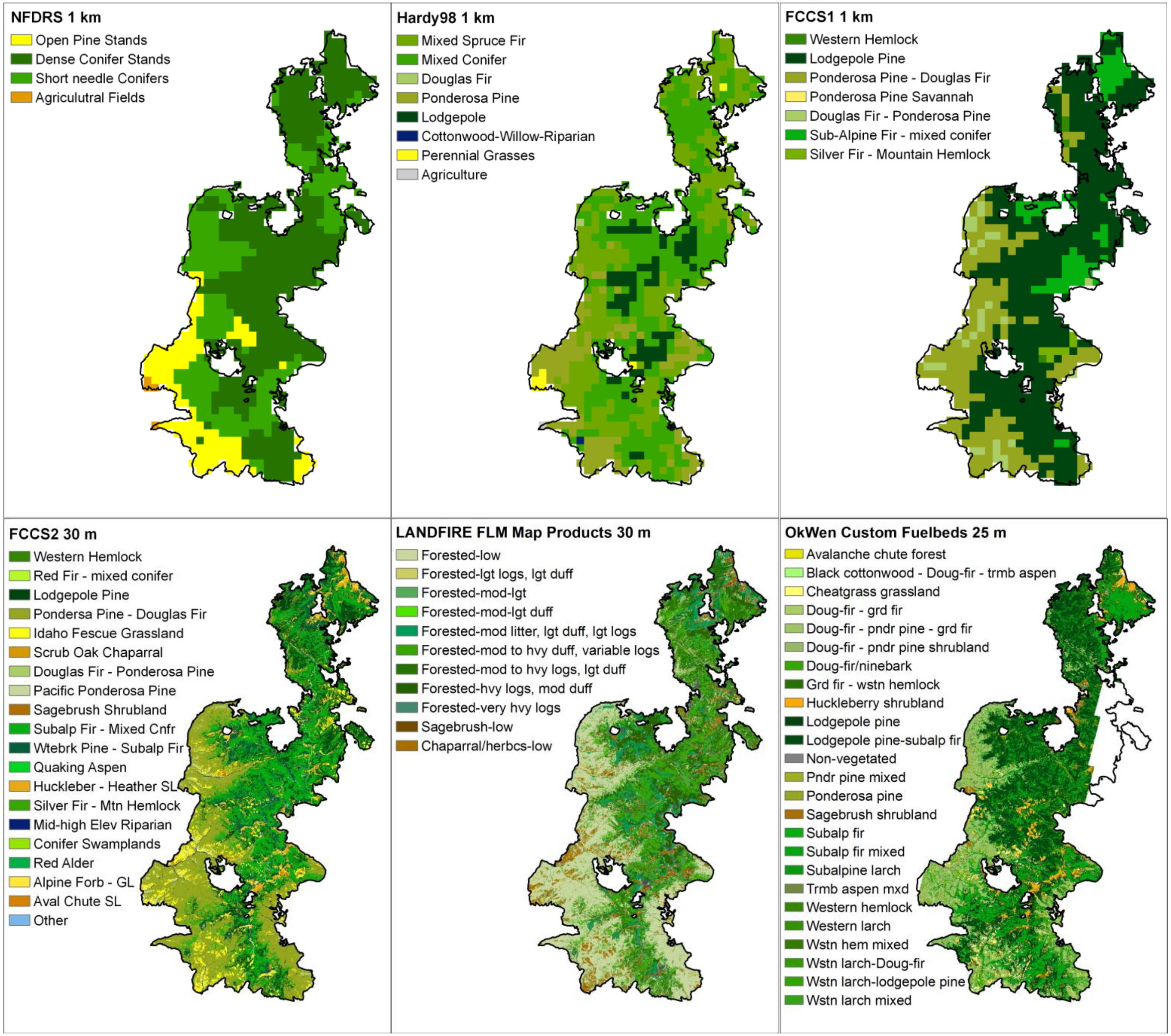

NFDRS 1 km
Open Pine Stands
Dense Conifer Stands
Short needle Conifers
Agriculutral Fields
Hardy98 1 km
Mixed Spruce Fir
Mixed Conifer
Douglas Fir
Ponderosa Pine
Lodgepole
Cottonwood-Willow-Riparian
Perennial Grasses
Agriculture
FCCS1 1 km
Western Hemlock
Lodgepole Pine
Ponderosa Pine - Douglas Fir
Ponderosa Pine Savannah
Douglas Fir - Ponderosa Pine
Sub-Alpine Fir - mixed conifer
Silver Fir - Mountain Hemlock
FCCS2 30 m
Western Hemlock
Red Fir - mixed conifer
Lodgepole Pine
Pondersa Pine - Douglas Fir
Idaho Fescue Grassland
Scrub Oak Chaparral
Douglas Fir - Ponderosa Pine
Pacific Ponderosa Pine
Sagebrush Shrubland
Subalp Fir - Mixed Cnfr
Wtebrk Pine - Subalp Fir
Quaking Aspen
Huckleber - Heather SL
Silver Fir - Mtn Hemlock
Mid-high Elev Riparian
Conifer Swamplands
Red Alder
Alpine Forb - GL
Aval Chute SL
Other
LANDFIRE FLM Map Products 30 m
Forested-low
Forested-lgt logs, lgt duff
Forested-mod-lgt
Forested-mod-lgt duff
Forested-mod litter, lgt duff, lgt logs
Forested-mod to hvy duff, variable logs
Forested-mod to hvy logs, lgt duff
Forested-hvy logs, mod duff
Forested-very hvy logs
Sagebrush-low
Chaparral/herbcs-low
OkWen Custom Fuelbeds 25 m
Avalanche chute forest
Black cottonwood - Doug-fir - trmb aspen
Cheatgrass grassland
Doug-fir - grd fir
Doug-fir - pndr pine - grd fir
Doug-fir - pndr pine shrubland
Doug-fir/ninebark
Grd fir - wstn hemlock
Huckleberry shrubland
Lodgepole pine
Lodgepole pine-subalp fir
Non-vegetated
Pndr pine mixed
Ponderosa pine
Sagebrush shrubland
Subalp fir
Subalp fir mixed
Subalpine larch
Trmb aspen mxd
Western hemlock
Western larch
Wstn hem mixed
Wstn larch-Doug-fir
Wstn larch-lodgepole pine
Wstn larch mixed

Figure 5

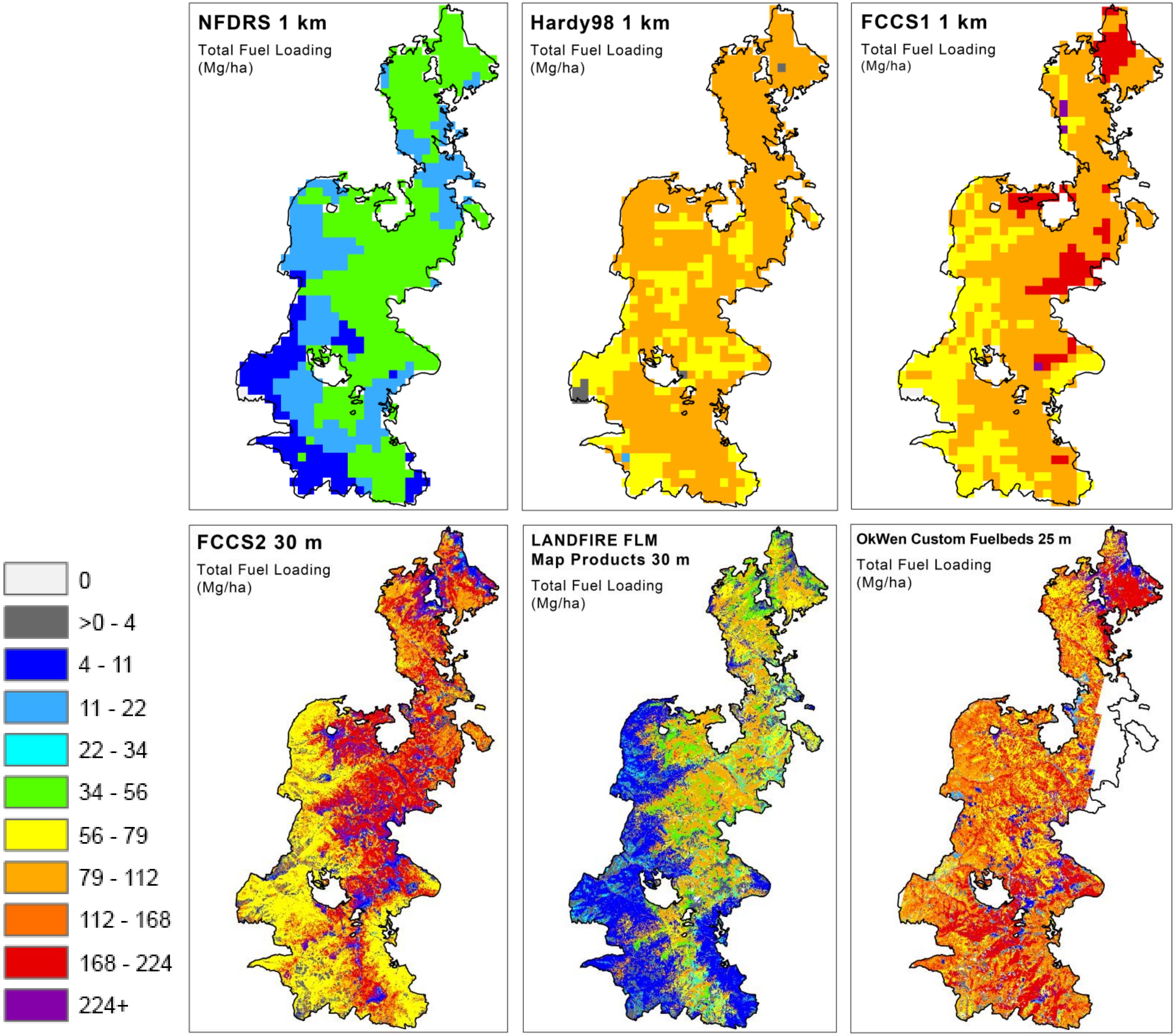

NFDRS 1 km
Total Fuel Loading (Mg/ha)
Hardy98 1 km
Total Fuel Loading (Mg/ha)
FCCS1 1 km
Total Fuel Loading (Mg/ha)
FCCS2 30 m
Total Fuel Loading (Mg/ha)
LANDFIRE FLM Map Products 30 m
Total Fuel Loading (Mg/ha)
OkWen Custom Fuelbeds 25 m
Total Fuel Loading (Mg/ha)
0
>0 - 4
4 - 11
11 - 22
22 - 34
34 - 56
56 - 79
79 - 112
112 - 168
168 - 224
224+

Figure 6

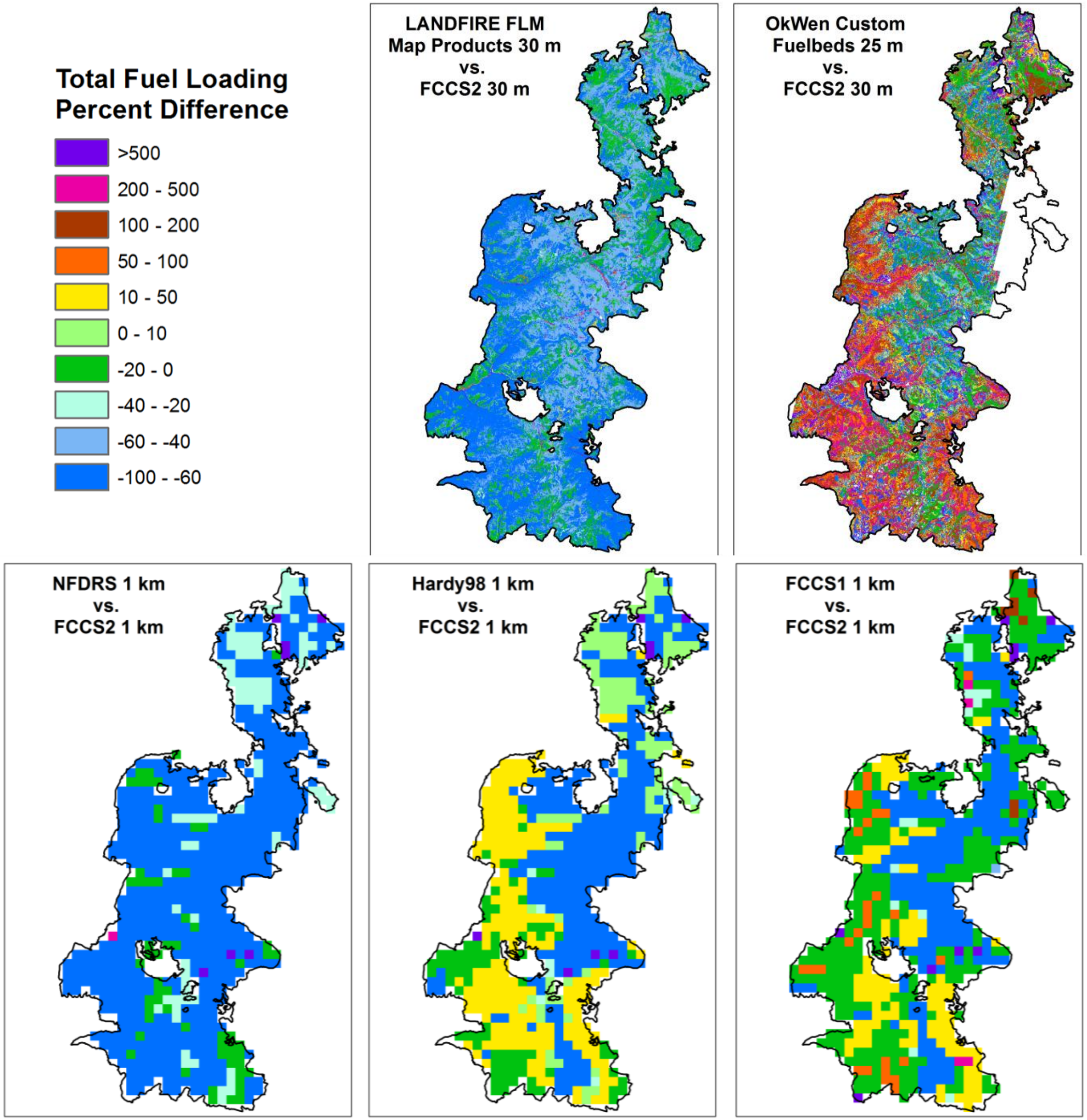

Total Fuel Loading
Percent Difference
>500
200 - 500
100 - 200
50 - 100
10 - 50
0 - 10
-20 - 0
-40 - -20
-60 - -40
-100 - -60
LANDFIRE FLM Map Products 30 m vs. FCCS2 30 m
OkWen Custom Fuelbeds 25 m vs. FCCS2 30 m
NFDRS 1 km vs. FCCS2 1 km
Hardy98 1 km vs. FCCS2 1 km
FCCS1 1 km vs. FCCS2 1 km

Figure 7

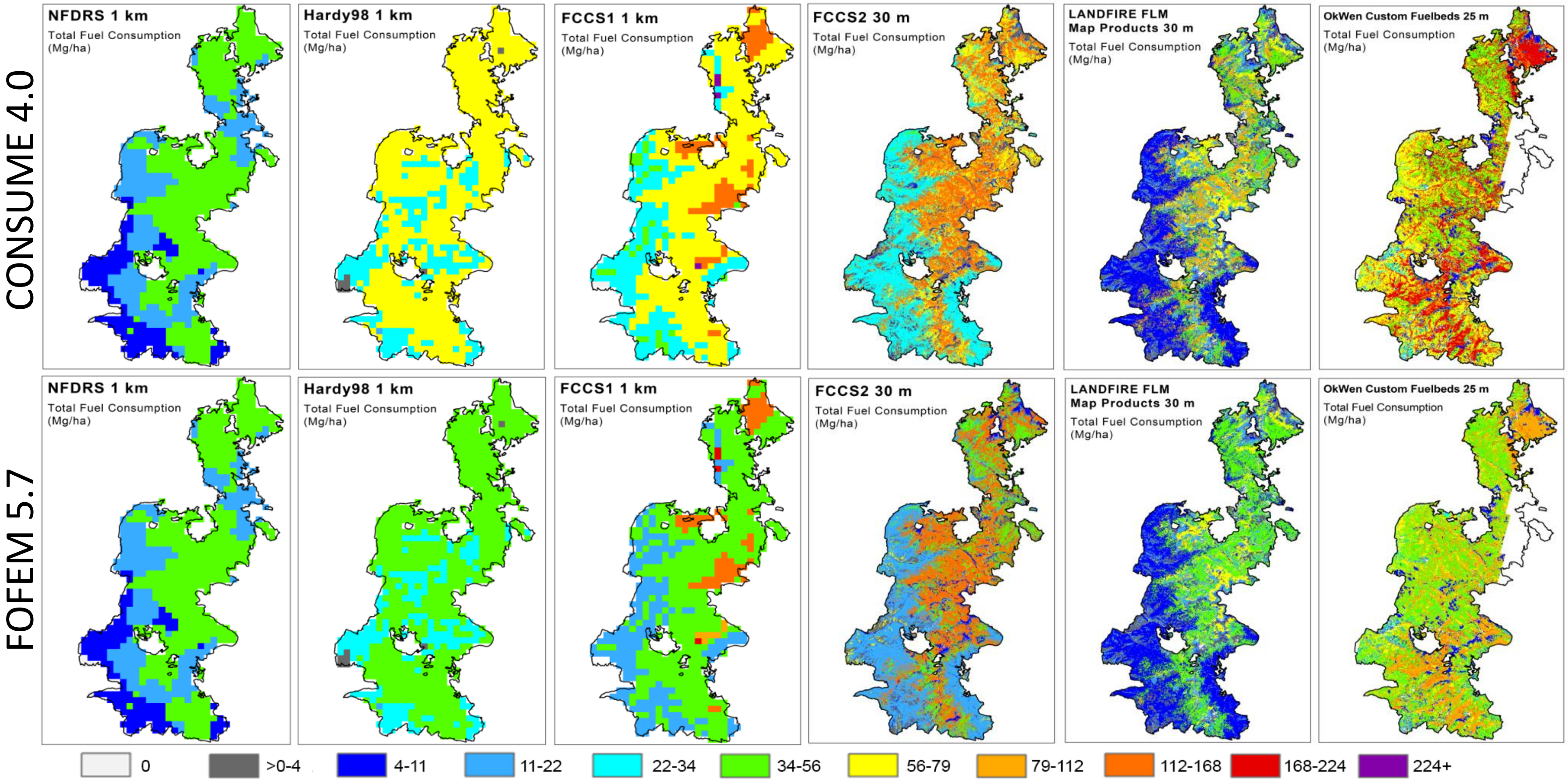

CONSUME 4.0
FOFEM 5.7
NFDRS 1 km
Hardy98 1 km
FCCS1 1 km
FCCS2 30 m
LANDFIRE FLM
Map Products 30 m
OkWen Custom Fuelbeds 25 m
Total Fuel Consumption
(Mg/ha)
0
>0-4
4-11
11-22
22-34
34-56
56-79
79-112
112-168
168-224
224+

Figure 8

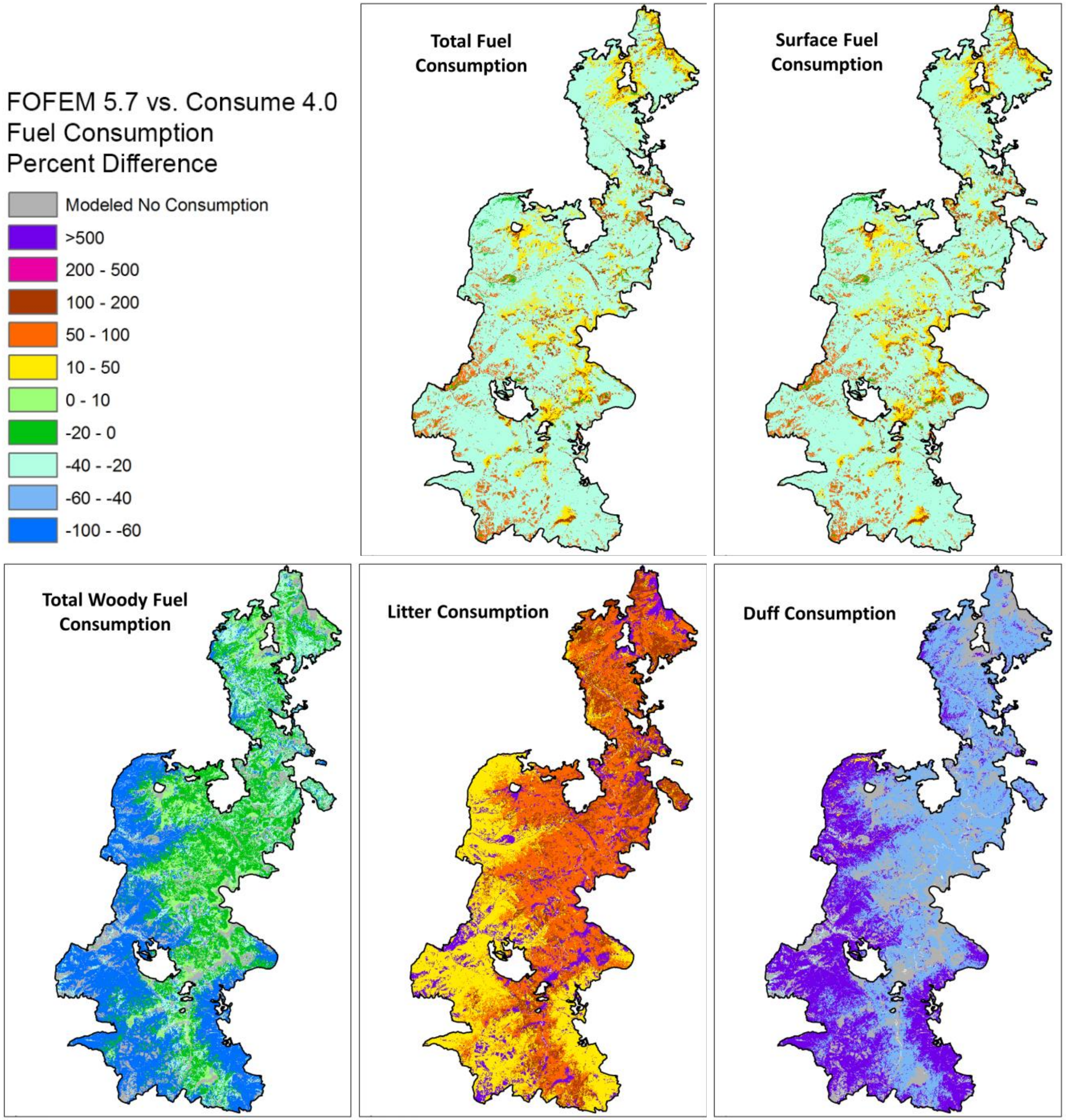
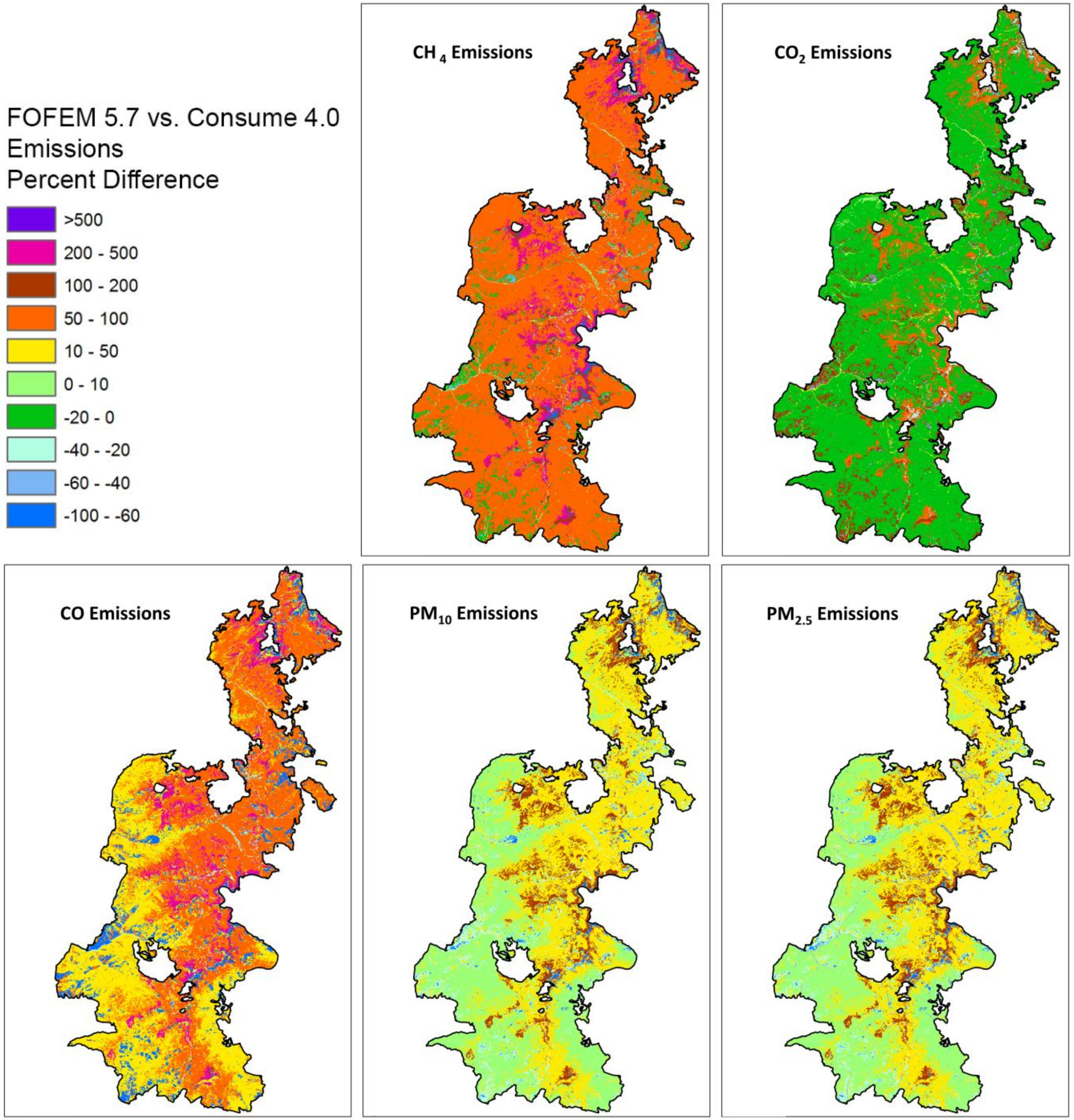
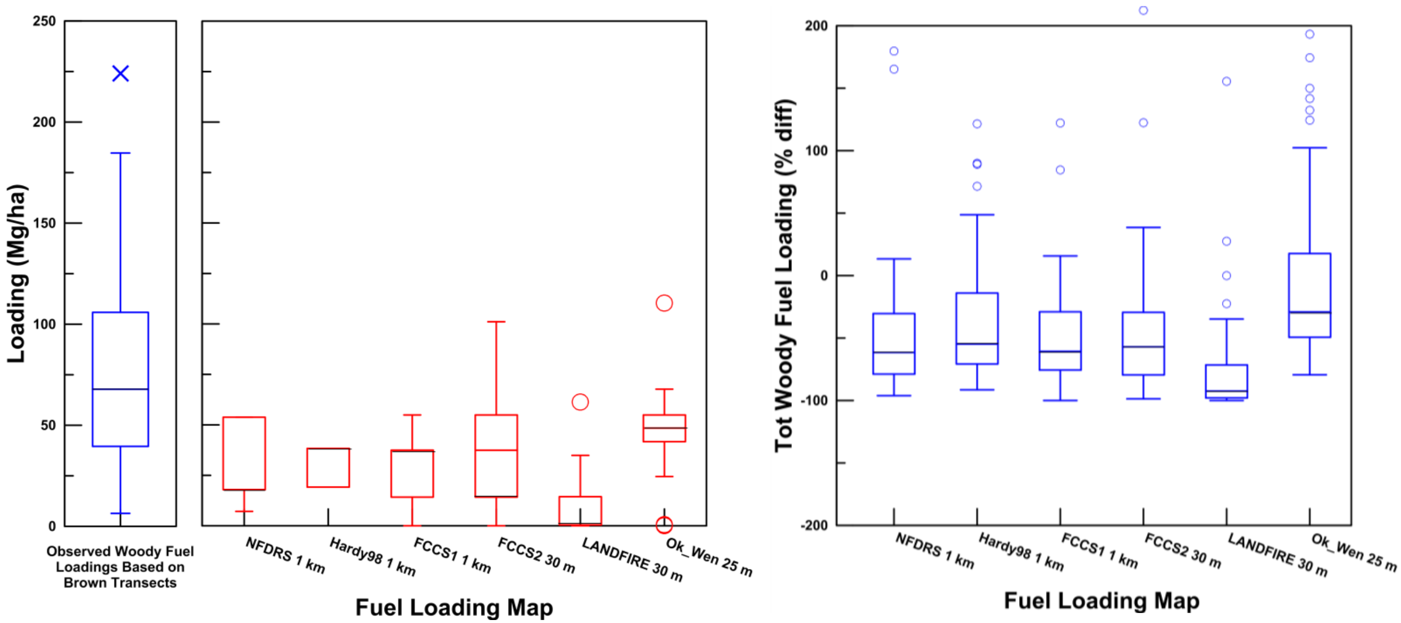

FOFEM 5.7 vs. Consume 4.0
Fuel Consumption
Percent Difference
Modeled No Consumption
>500
200 - 500
100 - 200
50 - 100
10 - 50
0 - 10
-20 - 0
-40 - -20
-60 - -40
-100 - -60
Total Fuel Consumption
Surface Fuel Consumption
Total Woody Fuel Consumption
Litter Consumption
Duff Consumption

Figure 9



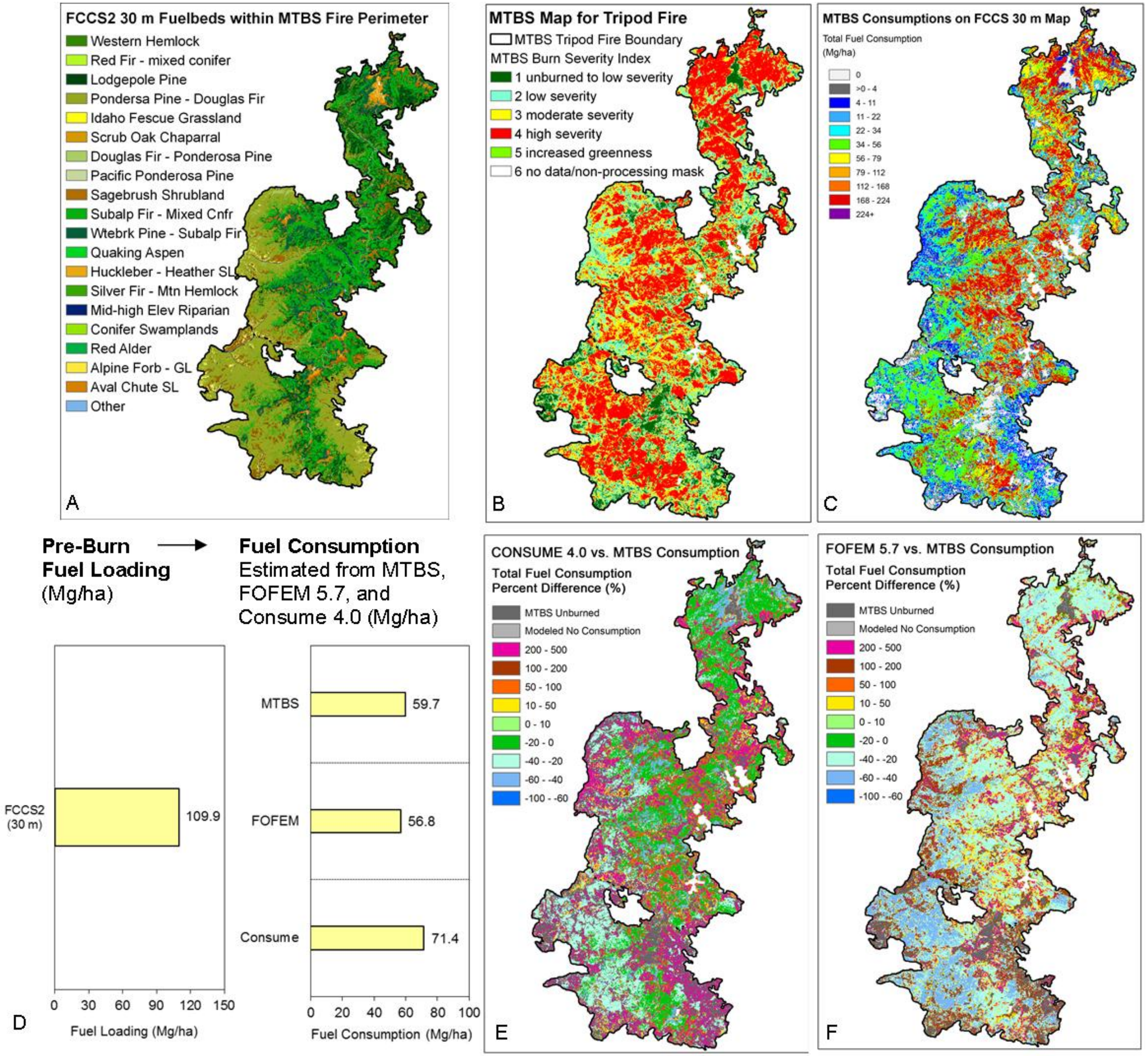
FOFEM 5.7 vs. Consume 4.0
Emissions
Percent Difference
>500
200 - 500
100 - 200
50 - 100
10 - 50
0 - 10
-20 - 0
-40 - -20
-60 - -40
-100 - -60
CH_4 Emissions
CO_2 Emissions
CO Emissions
PM_{10} Emissions
$PM_{2.5}$ Emissions

Figure 10



Loading (Mg/ha)
250
200
150
100
50
0
Observed Woody Fuel Loadings Based on Brown Transects
NFDRS 1 km
Hardy98 1 km
FCCS1 1 km
FCCS2 30 m
LANDFIRE 30 m
Ok_Wen 25 m
Fuel Loading Map
Tot Woody Fuel Loading (% diff)
200
100
0
-100
-200
NFDRS 1 km
Hardy98 1 km
FCCS1 1 km
FCCS2 30 m
LANDFIRE 30 m
Ok_Wen 25 m
Fuel Loading Map

Figure 11



FCCS2 30 m Fuelbeds within MTBS Fire Perimeter
Western Hemlock
Red Fir - mixed conifer
Lodgepole Pine
Pondersa Pine - Douglas Fir
Idaho Fescue Grassland
Scrub Oak Chaparral
Douglas Fir - Ponderosa Pine
Pacific Ponderosa Pine
Sagebrush Shrubland
Subalp Fir - Mixed Cnfr
Wtebrk Pine - Subalp Fir
Quaking Aspen
Huckleber - Heather SL
Silver Fir - Mtn Hemlock
Mid-high Elev Riparian
Conifer Swamplands
Red Alder
Alpine Forb - GL
Aval Chute SL
Other
A
MTBS Map for Tripod Fire
MTBS Tripod Fire Boundary
MTBS Burn Severity Index
1 unburned to low severity
2 low severity
3 moderate severity
4 high severity
5 increased greenness
6 no data/non-processing mask
B
MTBS Consumptions on FCCS 30 m Map
Total Fuel Consumption
(Mg/ha)
0
>0 - 4
4 - 11
11 - 22
22 - 34
34 - 56
56 - 79
79 - 112
112 - 168
168 - 224
224+
C
Pre-Burn
Fuel Loading
(Mg/ha)
Fuel Consumption
Estimated from MTBS, FOFEM 5.7, and Consume 4.0 (Mg/ha)
FCCS2
(30 m)
109.9
0 30 60 90 120 150
Fuel Loading (Mg/ha)
D
MTBS 59.7
FOFEM 56.8
Consume 71.4
0 20 40 60 80 100
Fuel Consumption (Mg/ha)
CONSUME 4.0 vs. MTBS Consumption
Total Fuel Consumption
Percent Difference (%)
MTBS Unburned
Modeled No Consumption
200 - 500
100 - 200
50 - 100
10 - 50
0 - 10
-20 - 0
-40 - -20
-60 - -40
-100 - -60
E
FOFEM 5.7 vs. MTBS Consumption
Total Fuel Consumption
Percent Difference (%)
MTBS Unburned
Modeled No Consumption
200 - 500
100 - 200
50 - 100
10 - 50
0 - 10
-20 - 0
-40 - -20
-60 - -40
-100 - -60
F

Figure 12

SEMIP Flowchart

Fire Information → **Pre-Burn Fuel Loading** → **Fuel Consumption** → **Emission**

Fire perimeter: **NIFC**
Area Burned: 70,821 hectares
FCCS2 30m fuelbeds displayed

Fuel Loadings of 6 vegetation models (Mg/ha).

(Mg/ha)
Consumptions estimated from Consume 4.0 and FOFEM 5.7.

Emissions of $PM_{2.5}$, PM_{10}, CO, and CO_2 (Mg/ha), estimated from Consume 4.0 and FOFEM 5.7.

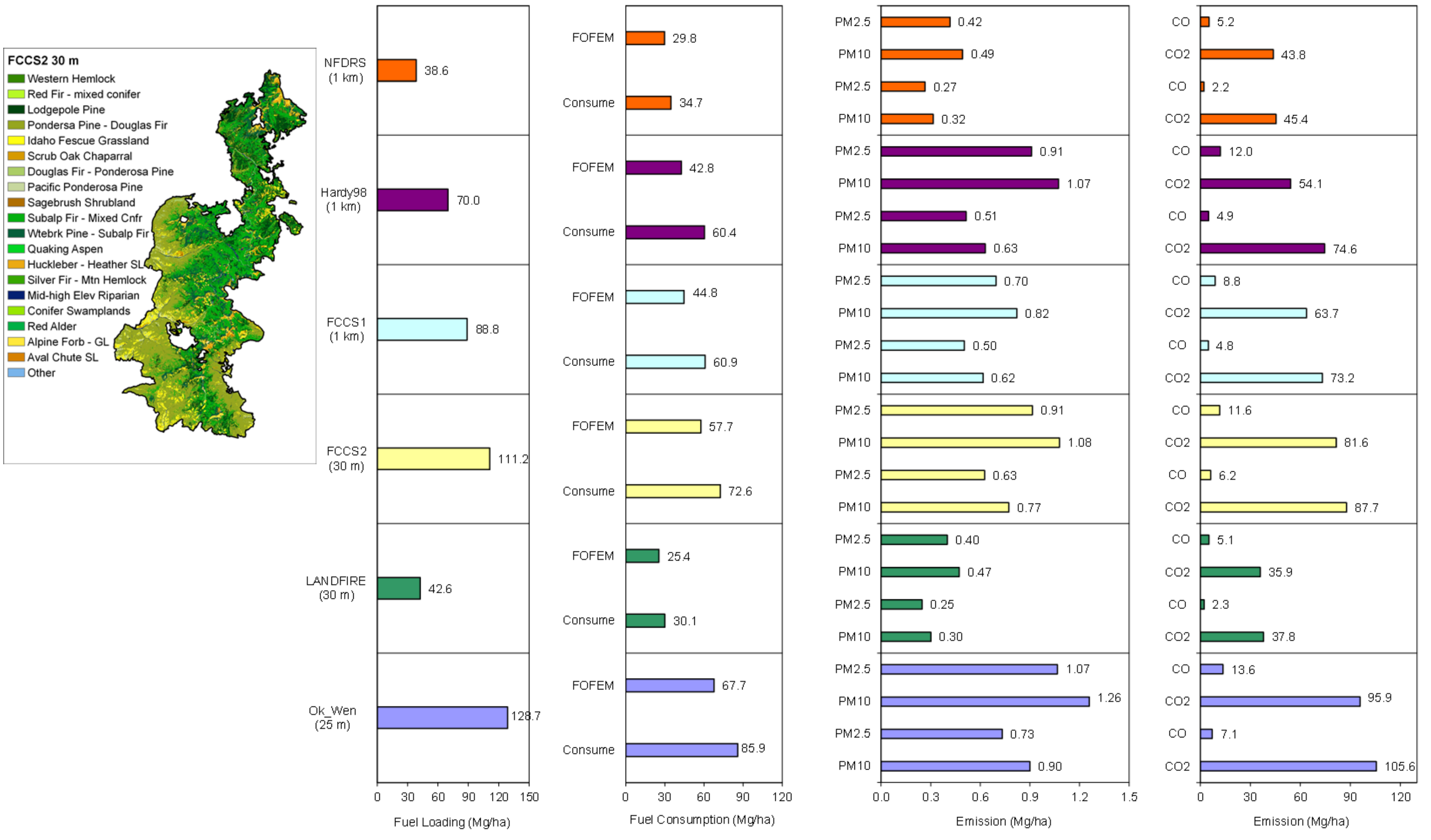


Figure 1. The modeling steps for which intercomparisons were performed for the smoke emissions modeling on the Tripod Fire Complex. The models, or systems, evaluated in this study are listed for each level.

Figure 2. The Tripod fire location and progression map. The weekly and final fire perimeters were acquired from the National Interagency Fire Center (NIFC).

Figure 3. Tripod fire complex size and perimeter for each of the five fire reporting system compared. The MODIS Burned Area product assumed the fire was a snow field and therefore produced a fire size of 0.

Figure 4. The vegetation maps outlined by the National Interagency Fire Center (NIFC) fire perimeter for the Tripod Fire Complex. 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 center and eastern sections of the fire area.

Figure 5. The total fuel loading maps outlined by the NIFC fire perimeter for the Tripod fire complex.

Figure 6. The percent difference in total fuel loadings. The fuel loadings of lower resolution vegetation maps (NFDRS 1km, Hardy 98 1km, and FCCS1km) were compared with FCCS2 1 km fuel loadings (top row). The higher resolution maps (LANDFIRE FLM 30 m and Okanogan-Wenatchee Custom Fuelbeds 25 m) were compared with FCCS2 30 m fuel loadings (bottom row).

Figure 7. Fuel consumption maps outlined by the NIFC fire perimeter for the Tripod fire. Consume 4.0 consumption maps are shown in the top row and FOFEM 5.7 consumption maps are in the second row.

Figure 8. The percent difference in fuel consumptions between estimates from FOFEM 5.7 and Consume 4.0. The FCCS2 30m map is used for modeling and display. Consume predicted higher consumption rates (negative differences) for total fuel and total surface fuel. Consume 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.

Figure 9. The percent difference in emissions estimates from FOFEM 5.7 and Consume 4.0. The FCCS2 30m 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.

Figure 10. 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.

Figure 11. Fuel consumptions estimated from the Monitoring Trends in Burn Severity (MTBS) linked to Composite Burn Index (CBI) and compared with Consume 4.0 and FOFEM 5.7 fuel consumption outputs. All results shown in this figure are based on the MTBS fire perimeter and FCCS2 30 m fuelbeds for the Tripod fire complex. The FCCS2 30 m vegetation (a), burn severity (b), and the corresponding fuel consumption calculated from burn severity and CBI (c) are displayed. The fuel loading and fuel consumptions estimated from MTBS, FOFEM, and Consume (d), and the differences (%) in fuel consumptions between MTBS and Consume, and MTBS and FOFEM (e) are also shown.

Figure 12. The outputs of the smoke emissions modeling pathway steps at a glance for the Tripod fire complex. Fire perimeter is from the National Interagency Fire Center (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 the sample map (left). The fuel consumptions and emissions for $PM_{2.5}$, PM_{10}, CO, and CO_2, were estimated using Consume 4.0 and FOFEM 5.7.

Tables

Table 1: Fuel strata available for each fuel loading map evaluated on the Tripod fire complex.

Fuel Stratum	**NFDRS 1km**	**Hardy98 1km**	**FCCS V1 1km**	**FCCS-LF 1km**	**FCCS-LF 30m**	**LANDFIRE 30m**	**OkWen 25m**
Live Tree Fuel Loading			x	x	x	x	x
Snag Fuel Loading			x	x	x		x
Stumps Fuel Loading			x	x	x		x
Shrub Fuel Loading	x	x	x	x	x	x	x
Herbaceous Fuel Loading	x	x	x	x	x	x	x
1 hr Sound Woody Fuel Loading	x	x	x	x	x	x	x
10 hr Sound Woody Fuel Loading	x	x	x	x	x	x	x
100 hr Sound Woody Fuel Loading	x	x	x	x	x	x	x
1000 hr Sound Woody Fuel Loading	x	x	x	x	x	x	x
10000 hr Sound Woody Fuel Loading		x	x	x	x		x
10000+ hr Sound Woody Fuel Loading		x	x	x	x		x
1000 hr Rotten Woody Fuel Loading			x	x	x	x	x
10000 hr Rotten Woody Fuel Loading			x	x	x		x
10000+hr Rotten Woody Fuel Loading			x	x	x		x
Litter Fuel Loading			x	x	x	x	x
Duff Fuel Loading		x	x	x	x	x	x

Table 2. Fuel moisture profiles from the Fire Emissions Prediction Simulator (FEPS Users Manual: Anderson et al. 2004).

Fuel Moisture Profiles (percent moisture)	1-hr Fuel Moisture	10-hr Fuel Moisture	100-hr Fuel Moisture	1000-hr Fuel Moisture	Live Fuel Moisture	Duff Fuel Moisture
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

Tables

Table 3. FOFEM 5.7 emission factors by pollutant (kg/Mg)

Combustion Phase	PM2.5	PM10	CO	CO2	CH4	SO2	NOx
Flaming	2.5	3	6.5	1778	1	1	3
Smoldering	22.5	26.5	301.5	1228	14	1	0

Tables

Table 4. Consume 4.0 emission factors by pollutant (kg/Mg)

Combustion Phase	PM2.5	PM10	PM	CO	CO2	CH4	NMHC
Flaming	6.5	7.5	11.5	45	1261	1.5	2.5
Smoldering	9.5	12	17	104.5	1142.5	5.5	5

Table 5. Summary table of fuel loading statistics (Mg/ha) aggregated by pixel for the NFDRS, Hardy98, FCCS1, FCCS2, LANDFIRE-FLM, and OkWen Custom. Fuel loading statistics include mean, max 3rd quartile, median, 1st quartile, and minimum value

	Total Fuel Loading (Mg/ha)					
	Mean	Max	3rd	Median	1st	Min
NFDRS 1 km	38.6	56.0	56.0	56.0	20.2	0.0
Hardy98 1 km	77.3	84.5	84.5	84.5	84.5	0.0
FCCS1 1 km	89.4	363.2	80.3	80.3	58.5	58.5
FCCS2 30 m	111.9	363.2	208.9	80.3	58.5	2.7
LANDFIRE FLM 30 m	43.5	168.4	91.2	25.3	9.4	1.8
OkWen Custom 25 m	133.4	479.5	207.6	121.5	74.4	0.2

Tables

Table 6. Fuel loading, fuel consumption, and emission data for the Tripod fire complex based on seven different vegetation maps. Fuel consumption and emissions were estimated using Consume 4.0 and FOFEM 5.7 for each map. Fuels are aggregated into total fuels, canopy fuels, total surface fuels, shrub, grass, total woody, sound woody, rotten woody, litter and duff categories.

Fuel Map	**NFDRS (1 km)**	**Hardy98 (1 km)**	**FCCS1 (1 km)**	**FCCS2 (1 km)**	**FCCS2 (30 m)**	**LANDFIRE (30 m)**	**Ok-Wen (25 m)**
# 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 Fuel Loading (megagrams)	2,718,590	4,931,377	6,315,591	8,792,675	7,875,389	3,017,456	8,367,184
Total Fuel Loading (megagrams/hectare)	38.6	69.9	88.8	123.3	111.2	42.6	128.7
Canopy Fuel Loading (megagrams)	0	0	1,367,157	2,496,356	2,224,207	505,622	2,565,159
Canopy Fuel Loading (megagrams/hectare)	0	0	19.3	35	31.4	7.2	39.5
Total Surface Fuel Loading (megagrams)	2,718,590	4,931,377	4,948,433	6,296,319	5,651,181	2,511,835	5,802,024
Total Surface Fuel Loading (megagrams/hectare)	38.6	69.9	69.5	88.3	79.8	35.4	89.2
Shrub Loading (megagrams/hectare)	1.1	1.1	0.2	0.9	0.9	0.7	1.6
Grass Loading (megagrams/hectare)	1.1	1.1	0.7	0.9	0.9	0.7	0.2
Total Woody Loading (megagrams/hectare)	36.1	33.6	32.5	37.7	34.5	15.7	48.6
Sound Woody Loading (megagrams/hectare)	36.1	33.6	25.6	22.6	20.8	9.9	36.3
Rotten Woody Loading (megagrams/hectare)	0	0	6.9	14.8	13.7	5.8	12.1
Litter Loading (megagrams/hectare)	0	0	3.8	4.0	3.8	2.9	3.8
Duff Loading (megagrams/hectare)	0	34.1	31.4	43.3	38.6	15.5	34.7

Fuel Consumption

Fire Effects Model	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM
Total Fuel Consumption (megagrams)	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 Fuel Consumption (tons/acre)	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 Fuel Consumption (megagrams)	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 Fuel Consumption (megagrams/hectare)	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 Fuel Consumption (megagrams)	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 Fuel Consumption (megagrams/hectare)	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 Consumption (megagrams/hectare)	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 Consumption (megagrams/hectare)	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 Consumption (megagrams/hectare)	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 Consumption (megagrams/hectare)	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 Consumption (megagrams/hectare)	0	1.6	0	2.2	5.8	4.3	12.8	11.7	11.4	10.8	5.8	4.7	10.1	9.4
Litter Consumption (megagrams/hectare)	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 Consumption (megagrams/hectare)	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

Emission

Fire Effects Model	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM	Consume	FOFEM
CH_4 (megagrams/hectare)	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 (megagrams/hectare)	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_2e (megagrams/hectare)	45.9	45.0	75.8	56.9	74.3	65.7	99.2	92.2	89.2	84.2	38.4	37.1	107.3	99.0
CO (megagrams/hectare)	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} (megagrams/hectare)	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

PM2.5 (megagrams/hectare)	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 (megagrams/hectare)	0.5		0.9		0.9		1.2		1.1		0.4		1.3	
NMHC (megagrams/hectare)	0.1		0.2		0.2		0.3		0.3		0.1		0.4	
NOX (megagrams/hectare)		0.04		0		0.04		0.1		0.1		0.02		0.1
SO2 (megagrams/hectare)		0.02		0.04		0.04		0.1		0.1		0.02		0.1

Table 7. Summary table of fuel consumption statistics for FOFEM 5.7 and Consume 4.0 (Mg/ha) aggregated by pixel for the NFDRS, Hardy98, FCCS1, FCCS2, LANDFIRE-FLM, and OkWen Custom. Fuel loading statistics include mean, max 3rd quartile, median, 1st quartile, and minimum value

		Total Fuel Consumption (Mg/ha)					
		Mean	Max	3rd	Median	1st	Min
Consume 4.0	NFDRS 1 km	34.7	50.4	50.4	50.4	17.9	0.0
	Hardy98 1 km	60.3	71.1	71.1	71.1	71.1	0.0
	FCCS1 1 km	61.4	288.1	58.7	58.7	29.4	29.4
	FCCS2 30 m	73.1	288.1	159.2	58.7	29.4	1.6
	LANDFIRE FLM 30 m	30.7	126.2	70.8	18.2	5.2	1.6
	OkWen Custom 25 m	89.7	299.9	171.9	63.2	49.1	0.2
FOFEM 5.7	NFDRS 1 km	29.8	43.5	43.5	43.5	14.6	0.0
	Hardy98 1 km	42.8	48.4	48.4	48.4	48.4	0.0
	FCCS1 1 km	45.1	211.6	43.0	43.0	22.2	22.2
	FCCS2 30 m	58.1	211.6	112.3	43.0	22.2	2.7
	LANDFIR- FLM 30 m	25.8	132.5	47.7	15.0	4.9	1.1
	OkWen Custom 25 m	68.4	256.2	111.0	54.7	37.2	0.2

Table 8. Summary table 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	12,322,606 Mg	8,503,708 Mg	106,574 Mg
70,837 hectares	3,017,456 Mg	1,796,054 Mg	17,467 Mg
Difference of 28,208 hectares	Difference of 9,305,150 Mg	Difference of 6,707,654 Mg	Difference of 89,107 Mg
33% Percent Difference	121% Percent Difference	130% Percent Difference	144% Percent Difference

**Although NFDRS had the lowest absolute fuel loadings, the LANDFIRE FLM pathway was used in this stage of the minimum possibilities pathway as the NFDRS did not include multiple fuel strata.