

FINAL REPORT

Title: Mapping Fuels for Regional Smoke
Management and Emissions Inventories

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Abstract

Fuels are highly variable and dynamic in space and time, and fuel loading can vary considerably even within fine spatial scales and within specific fuel types, such as downed wood or organic soils. Given this inherent variability in fuel loadings, it is not good practice to represent all instances of a fuel type by the same set of fuel loadings, as these vary at multiple spatial scales and are generally independent of each other. The best practice for producing emissions estimates from data with inherent variability is to represent the underlying uncertainty in the base fuels data. This measure of uncertainty can then be used in understanding the reliability of the fuel-loading estimates and also to evaluate how that uncertainty propagates to variability in emissions estimates. Models for emissions inventories are becoming increasingly sophisticated and require corresponding complexity in input datasets – the appropriate probability distributions of their base layers rather than just their means. No such datasets exist for fuels despite their acknowledged variability at multiple spatial scales. In response to the JFSP 2015 FON Task Statement 1 “Fuels mapping for emissions inventories”, our multi-institutional team completed a project to improve information on fuel loadings valuable for fire and smoke management by compiling data on fuel loadings for fuels across the Conterminous US and Alaska and then calculating the variability in fuels found in this existing field data.

In this project, we: (1) developed probability distributions of fuel loadings for US fuelbeds using existing field data; (2) created geospatial fuel layers with enhanced fuel loading information that can be used by the emissions modeling and inventory communities in the United States; and (3) conducted a sensitivity analysis based on the compiled data to evaluate sources of uncertainty and data gaps for emissions estimates. This study was informed by results of the Smoke and Emissions Model Intercomparison Project (SEMIP) funded by the Joint Fire Science Program, which showed that fuel loadings introduce most of the uncertainty in emissions modeling. The final dataset was created by consolidating existing data records on fuel loadings from many sources of field data describing wildland fire fuels in North America. The resulting database, called the North American Wildland Fuels Database (NAWFD; French et al. 2020) can be accessed through a data access application web site available at <https://fuels.mtri.org>. NAWFD aggregates fuel loading information from 26,620 field sites compiled from 271 data sources. Each data point is assigned to a LANDFIRE Existing Vegetation Group ID (EVT; <https://www.landfire.gov/evt.php>). Probability distributions have been generated for each fuel stratum within each fuelbed. The EVT Groups served as a means to combine vegetation types that did not have enough data for statistical description. NAWFD was developed to enable best practices for modeling national- and regional-scale fire emissions by incorporating uncertainty into fuels estimates used in smoke emissions modeling. The database and probability density functions created for each EVG were used to analyze the sensitivity of emissions estimates to fuel loading variability. Additional work included a comparison of the fuels distributions to data held out of the database to validate the distributions against field-collected data for a selection of fuelbeds, and an effort to identify gaps in existing data on fuel loading to prioritize field data collection for minimizing uncertainty in emissions modeling.

Objectives

Our goal for this project was to develop a geospatial database of fuels that enables best practices for representing fuel loading in models of national- and regional-scale emissions. Our work is built on the premise that a map of fuels suitable for regional emissions modeling must be constructed at a coarse spatial resolution (1-km or more); maps can never represent plot-level observations precisely due to the heterogeneity of fuels at this scale. Best practices for regional emissions modeling must therefore employ fuel layers that characterize variability of fuel loading, and that have been informed from field sampling.

The Project Objectives were three-fold and accomplished via three complementary tasks, as described below:

- *Methodological development*: Develop a robust and repeatable method of mapping and validating fuel-loading distributions for emissions modeling based on existing field data.
- *Product creation and access*: Create a set of geospatial fuel layers that can be used by the emissions modeling and inventory communities in the US to assess wildland fire emissions and their variability under a range of relevant scenarios, and develop a tool to provide access to the fuel data layers and to visualize sources of uncertainty in emissions inventory maps.
- *Assessment of fuels in emissions models*: Evaluate sources of uncertainty and data gaps for emissions estimates using a sensitivity analysis of emissions models to fuel variability informed by distributions of fuel characteristics.

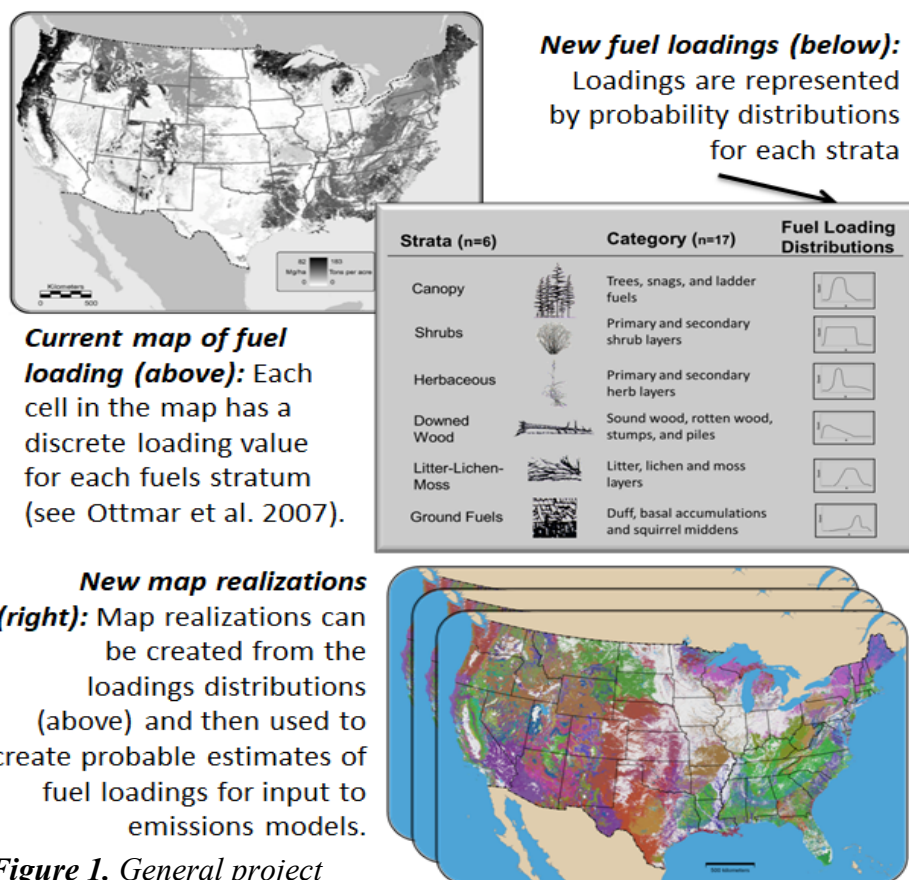


Figure 1. General project plan showing the concept for this project.

The JFSP task statement requested an assessment of the most effective combination of tools to map fuels and calculate emissions for emissions inventories. Currently, there are a large number of tools and products available within the US for fire-emissions inventory mapping and monitoring. The most common and accepted approaches for emissions modeling, however, use the same fundamental approach, and many use the same or very comparable tools and information sources. None of the approaches employ metrics of fuel loading variability or data error metrics suitable for uncertainty assessment. The project proposed included data compilation and analysis to provide an assessment of variability suitable for use in several operational emissions models as well as regional- to global-scale smoke modeling efforts.

All project objectives were met in our project period. A national-scale assessment of fuel loadings was compiled, and a data access system developed. realizations of mapped fuel loadings can be created within the system, and data-derived fuel loading probability density functions are available at the site: <https://fuels.mtri.org> (**Figure 1**). The results provide a statistically accurate characterization of representative fuelbeds and loadings for national emissions inventories and other broad-scale applications based on existing data and resources.

Background

The JFSP-funded Smoke and Emissions Model Intercomparison Project (SEMIP; Larkin et al. 2012) found that fire emissions calculations are most sensitive to fuels information (as opposed to the other major emissions-model components: fire information, consumption model assumptions, and emissions factors). Our project builds from results of the SEMIP project by creating improved fuels maps and optimizing approaches to best estimate wildland fire emissions.

The current wildland fire emissions inventory included in the Environmental Protection Agency's 2011 National Emissions Inventory (NEI; <http://www.epa.gov/ttnchie1/net/2011inventory>) is derived from a map of fuelbeds defined by the FCCS (<http://www.fs.fed.us/pnw/fera/fccs>). To quantify biomass burning activity for forests and agricultural fires, the fuels map is used in conjunction with spatial fire occurrence data and modeled estimates of fuel consumed using the Consume model (Ottmar 1993, Prichard et al. 2007, Raffuse et al. 2012). For application in atmospheric modeling, fire emissions are calculated by the FINN model (Fire Inventory from NCAR, <https://www2.acd.ucar.edu/modeling/finn-fire-inventory-ncar>). FINN employs a set of generic land-cover categories to define fuels and compute emissions from biomass burning (Wiedinmyer et al. 2011). The coarse-scale maps used for these applications are limited in that they ignore the underlying variability of fuels.

Fuels are highly dynamic over space and time (Keane et al. 2012). It is impossible, however, to map fuels over an entire continent at the characteristic scales at which they vary. We therefore rely on classifications of fuels such as the FCCS (Ottmar et al. 2007) that characterize a discrete set of fuel types to produce fuels maps with estimates of fuel loadings. These maps summarize fuel characteristics at relatively coarse scales (1-km pixels) that aggregate finer-scale variability and provide point estimates of fuel characteristics over the discrete set of fuel types. Underlying those classifications, however, is variability in fuel loadings that is not acknowledged, much less quantified.

Given the inherent variability in fuel classifications, it is not informative to validate individual pixels in a continental-scale fuel map using plot-level data that may not represent the full pixel – such a validation will inevitably fail. Nor is it defensible to represent all instances of a fuel type by the same set of fuel loadings, as these vary at multiple spatial scales and are generally independent of each other (e.g., canopy fuel loadings and 1000-hr fuel loadings are

uncorrelated in most places; Raymond et al. 2006, McKenzie et al. 2007, Keane et al. 2012). The best practice for producing emissions estimates from data with inherent spatial variability is to represent the underlying uncertainty in the base fuels map. This measure of uncertainty can then be used in understanding the reliability of the fuel-loading estimates and also to evaluate how that uncertainty propagates to variability in emissions estimates. If it is found that emissions estimates are particularly sensitive to certain fuel categories in a major vegetation type (e.g., forest floor loadings in boreal forests), then the results of the sensitivity analysis will help guide future field sampling to provide a finer-scale characterization of those fuel categories. If the estimated emissions in some fuel categories are insensitive to uncertainty, then a default representation (e.g., a mean value) is likely adequate.

For many modeling projects the importance of incorporating variability is understood. For example, coarse-scale dynamic vegetation models draw inputs from probability distributions in order to model stochastic processes of fire and climate (Quillet et al. 2010). Models for emissions inventories are becoming increasingly sophisticated and require corresponding complexity in input datasets – the appropriate probability distributions of their base layers rather than just their means. No such datasets exist for fuels despite their acknowledged variability at multiple spatial scales (Keane et al. 2012).

With the exception of FINN, current emissions models use the 1-km mapped FCCS fuelbeds to represent fuel loadings across the US. FCCS fuelbeds were developed to capture the spatial and temporal variability and complexity of wildland fuels (Ottmar et al. 2007). The 1-km fuelbed map includes fuelbeds that represent major vegetation types in the US and is aggregated from a 30-m fuelbed map layer for the CONUS (McKenzie et al. 2012). A total of 245 forest, rangeland and other wildland fuelbeds were identified via a crosswalk from the LANDFIRE Existing Vegetation Types (EVT; <https://www.landfire.gov/evt.php>). For CONUS, 45 fuelbeds represent 90% of the vegetated land area in the US. FCCS fuelbeds are organized into six strata: canopy, shrub, herbaceous, downed wood, litter-lichen-moss, and ground fuels. Strata are further divided into 17 main categories (**Figure 1**). WFEI leverages the Fuel Loading Models (FLM), which complement the information provided in the FCCS (Urbanski et al. 2011). With the exception of FINN, consumption and emissions are modeled using either Consume or the First Order Fire Effects Model (FOFEM, Albini and Reinhardt 1997) or both. Consume and FOFEM are currently in the process of being integrated because they share many of the same inputs, complementary consumption algorithms, and similar emissions factors (Prichard et al. 2014).

The aim of this project was to develop a database that represents the inherent spatio-temporal variability in US-wide fuels. Current products used in fire emissions modeling are non-varying, with the exception of the newly created map of FCCS canopy fuel loadings (<http://www.fs.fed.us/pnw/fera/fccs/maps.shtml>) developed with the aid of remote sensing, specifically the MODIS Vegetation Continuous Fields (VCF), which contains information on canopy cover. The product was used to refine the canopy loadings of the base 1-km CONUS FCCS map. This approach provides the desired spatial variation in fuels we are seeking in the proposed project, but only for the canopy. The remote sensing approach cannot be successful for below-canopy strata, however, because satellites do not “see” below the canopy, and despite many attempts to get below-canopy fuels by regressions or imputations, these largely have failed (Raymond et al. 2006). Our proposed approach leveraged the extensive catalog of existing field-measured loadings to characterize loadings statistically for the variety of fuel types present across the US.

Materials & Methods

Study design

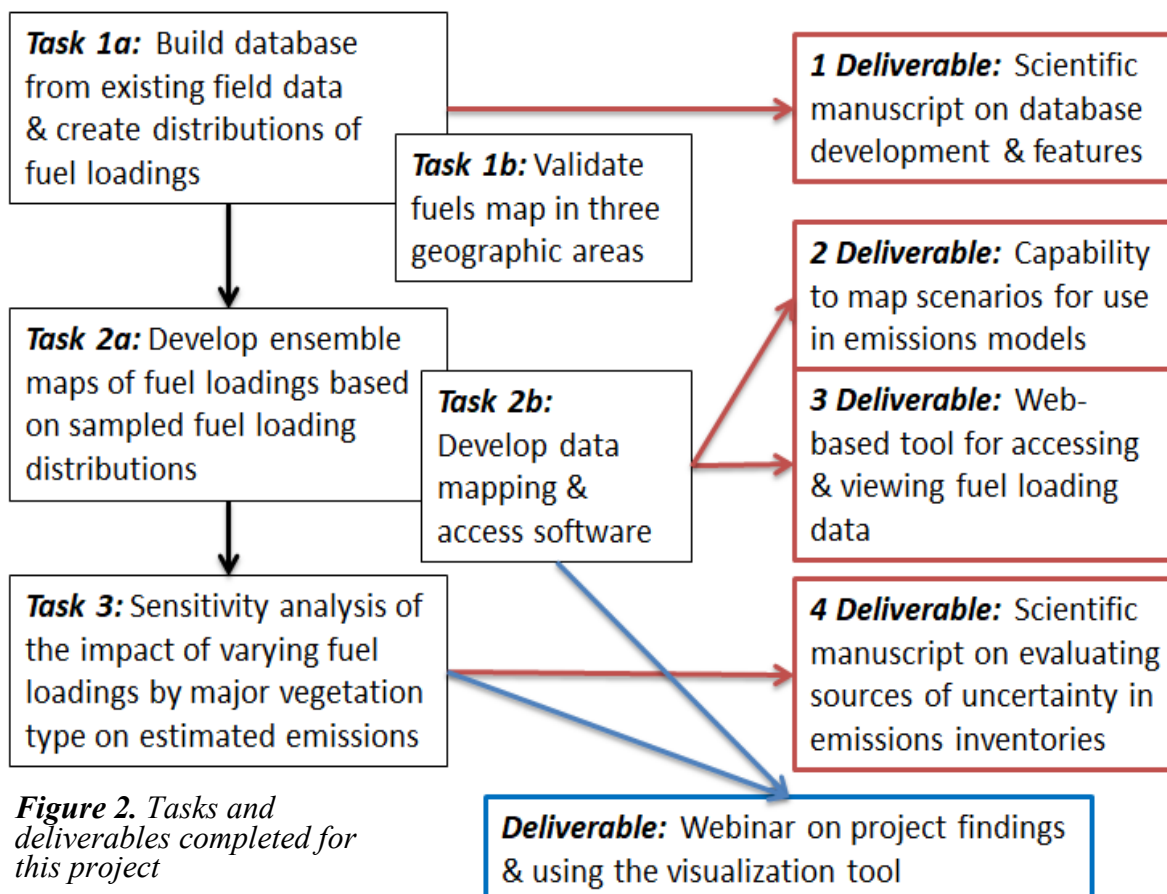
The project completed three main tasks (**Figure 2**). These tasks remained essentially the same from the proposed research plan. The original plan was to complete four deliverables. As the project progressed, these deliverables were modified to result in the products shown in **Figure 2**. The changes to these deliverables are fairly minor and are described in the results and discussion section. The project team was generally unchanged from the start of the project.

Research domain & study sites

The scope of this project was to develop a US-wide (Conterminous US (CONUS) and Alaska (AK)) characterization of fuels relevant for emissions inventories. Fuels data from across the US were the primary input to the database and analysis activities, although data from boreal Canada were also included, since these sites are represented across the boreal region including Alaska. Field data have been collected in all major vegetation types that have the potential for fire for a variety of efforts. Field data in some types are not as complete as in others, but for types that are fire adapted and fire-prone, extensive field sampling data are available (see Task 1).

Three test sites, representing distinctly different geographic areas, were chosen for a validation demonstration (Task 1b), although data for only two were found to be useful for the task. They are Savannah River Site (South Carolina) and sage-steppe ecosystems of the Great Basin (Intermountain West). The boreal Alaska data sets were not structured properly for validation work.

Table 1: Major data sources of the North American Wildland Fuel Database.



Source Name	Description	N
FIA loadings database	Forest Inventory and Analysis Program (2010), compiled and summarized by David Chojnacky, Virginia Tech University	13964
Public LFRDB	The LANDFIRE Reference Data Base (LFRDB; https://www.landfire.gov/lfrdb.php)	8017
FLM database	Source data for the fuel loading model development (Lutes et al., 2009)	1442
FOFEM fuels	Old database compiled to inform FOFEM fuel loading profiles (D. Lutes, pers. comm.)	917
Digital Photo Series database	Online database of natural fuels photo series sites (Wright and Eagle 2007)	463
FFS database	Fire and fire surrogates (McIver et al. 2009)	339
Other	Published literature	1478

Task 1: Compile a fuels database

Within Task 1 we compiled and assessed currently available fuels characterization data sets for creating the fuel-loading distributions and for using in Task 3 for testing emissions calculation sensitivity.

Task 1a: Build database from existing field data; create distributions of fuel loadings

We used existing field datasets to create a geodatabase of fuelbeds and fuel-loading distributions by major vegetation type, fuel stratum, and category. We began by compiling existing databases and importing wildland fuel biomass in a standard unit of measure (Mg/ha). Existing databases, including the source data for fuel loading models (Lutes et al., 2009) and Landfire public source reference database (LFRDB; <https://www.landfire.gov/lfrdb.php>) were compilations of published literature and plot data (Table 1). We next conducted a literature review of biomass, fuel characterization and fuel consumption literature and added observations from over 150 individual references.

As the database was assembled, we performed a series of quality-assurance and control measures. We first screened any records that were not georeferenced. For each of these records, we attempted to assign a geospatial location and standardized existing location data into latitude and longitude (decimal degrees). In some cases, it was necessary to assign site locations based on site descriptions. Many records ($n = 2470$) had geospatial location but no associated vegetation type or information. For these, we overlaid record locations with the EVT Groups layer in ArcGIS and assigned a likely EVT Group based on spatial location. Due to the potential errors incurred by spatial assignment, we tagged each of these records as having spatially assigned EVT group. In many instances, simple summations were required to create summary inputs (e.g., herb load was calculated as the sum of forb and graminoid biomass and total coarse woody debris (CWD) is the sum of all sound and rotten coarse wood classes).

The database includes data from 271 sources from existing databases and scientific literature. Entries from existing databases were presumed to be quality checked by the source agency and were not rechecked. As part of data entry and QA/QC, source references were carefully reviewed to ensure that they were not duplicative. We obtained the source reference and included a full citation for every record that had a published source reference. For quality assurance and quality control, we subsampled 30% of all source references and confirmed that entered data were accurate by cross checking entries with published values. Errors were uncommon; of records with data entry errors, most were simple rounding errors and were corrected. In a few cases, some fuel categories were missing from the inputs and were added from the published source. In

other cases, fuel categories were inaccurate and corrected within the database entries. We also flagged any extreme outliers in the database as observations in an EVT group (see section 2.5). These individual records were checked from the source data and any errors in recording were corrected. Otherwise the outliers were retained in the database. Many fuel categories are sparsely populated but are included because they are important within particular EVT groups. For example, moss and ground lichen are important in many boreal and sub-boreal vegetation types but are relatively rare in other ecosystems and associated EVT groups.

Fuel loadings were assembled into a relational database and used to calculate empirical distributions of loadings for each fuel strata (e.g., 100-hr fuels) for each major fuelbed type, based on the LANDFIRE Existing Vegetation Type (EVT) groups. Database values were clustered by LANDFIRE EVT group for estimation of biomass distributions. All analyses were conducted in the R statistical program (version 3.4.1; R Core Team, 2017), and distributions were estimated using the R *fitdistrplus* package (Delignette-Muller & Dutang, 2015). Histograms, boxplots, and normal QQ plots were used to understand prominent distribution shapes and to assist in QA/QC of the database. Due to these features, we chose a hurdle estimation procedure, described in Prichard et al. (2019). Further details of the methods for this task, including distribution assessment and testing, are provided in Prichard et al. (2019) (Deliverable 1 in Fig. 2).

Task 1b: Validate fuels data for emissions inventories

For Task 1b we set out to demonstrate a robust methodology for validation of the fuel maps and data sets, but found that a spatial assessment was not valuable nor informative. At the proposal stage, we had considered the idea of mapping the fuels in space as an important aspect of the project, however, fuels mapping is the work of the LANDFIRE program, so any additional work with this project would be unnecessarily repeating a very timely and costly task. Therefore, while the intention was a spatial fuel loading validation task, the actual validation was non-spatial, with the idea that any map validation exercise is within the purview of LANDFIRE and beyond the scope of this project.

With the modification to the task in mind, we set out to use data from the three sites identified at the proposal stage for validating the fuel loading database content (data collected in Task 1a). We found the data from two of the sites amenable to the task (Table 2), while the data from Alaska were not. We looked for other data sets for the boreal region, and investigated data collected and compiled for the NASA ABoVE program (<https://above.nasa.gov/>), but this dataset also was difficult to use. Multiple records with zero entries and a bias to recently burned sites made the data a poor choice for representing the type. We therefore conducted the analysis for two of the sites proposed, the Savannah River Site (SRS; Parresol et al. 2012) and the Sagebrush Steppe Treatment Evaluation Project (SageSTEP; McIver et al. 2010), which have data representing a range of EVT Groups representative of the southeast and western ecological regions.

Table 2: Sites with intensively-sampled field data used in validation of fuel loadings.

Site type(s)	Location	Description	Study Name	Study reference
Southern pine and upland hardwoods	Savannah River Site, SC	625 forest inventory plots including surface fuel loadings	SRS inventory	Parresol et al. 2012
Sagebrush Steppe	Great Basin	1530 sampling plots across 18 locations	SageSteppe	McIver et al. 2010 RMRS-GTR-237

The validation activity uses the Existing Vegetation Type (EVT) Groups to categorize the validation sites by vegetation cover type. The fuel loading for each stratum is compared between the validation datasets and the fuel loading database. The strata are overstory, midstory, understory, tree crown, snag, shrub, herbaceous, fine woody debris, coarse woody debris, lichen, moss, litter, litter, and duff, and downed, sound, and rotten woody debris in the timelag classes of 1-hr, 10-hr, 100-hr, 100-hr, 1000-hr, and greater than 1000-hr. The database also includes litter and duff depths. Not all database entries or validation plots include all strata.

Within each dataset, unburned or control plots were selected. Each dataset has estimated fuel loading and fuel depth for various strata. This data was converted in Mg/ha and cm respectively, which are the units from the database. To compare fuel loading between the validation data and the database, the strata of the validation dataset was crosswalked to the strata in the database and assigned the appropriate EVT Group. EVT Groups were assigned based on the dominant species and geography of the individual plot.

Task 2: Develop an approach to represent variability in fuel loadings

The products developed in Task 1 provide a means for including the variability of fuel loading as an input to models that include fuel loading as a model parameter. The data distributions were computed for data grouped by LANDFIRE Existing Vegetation Type (EVT) group, which provides the ability to map fuel loading variability using LANDFIRE products.

Task 2a: Develop ensemble maps of fuel loadings based fuel loading distributions.

Many disciplines, including the climate-modeling community, use ensemble model runs to predict complex natural phenomena. These model ensembles provide both point estimates and plausible ranges of model outputs given the underlying uncertainty in input data; no single run result is “correct”, but each is plausible based on the use of the loadings distributions developed for each fuelbed and each stratum in Task 1 (see **Figure 1**). Using the empirical distributions of fuel loadings from Task 1, we fit parametric distributions for EVT groups, allowing a probabilistic realization of fuel loadings by strata that can be mapped based on EVT group. Each realization of the US fuel map involves multiple draws from these distributions to populate each instance of the associated fuelbed. In this way, each cell on the map will have a different set of fuel loadings for each realization, but will be a representative sample each time of the expected distribution of fuel loadings, and the variance across instances will also match the distribution. Note that the map currently in use is a non-random realization, in which fuel loadings in all instances of a fuelbed are defined by the mean of the data and are all the same and thereby is misrepresenting their actual value by not accounting for inherent variability within fuelbed type.

The rich data set developed in Task 1 provides an opportunity to quantify the range of fuel loadings found in regions of the US. These data can then be mapped for use in smoke and emissions modeling. Regional emissions and air-quality models typically run at a grid spacing of 1 km or larger (Larkin et al. 2009, Wiedinmyer et al. 2011, French et al. 2014). The data compiled and analyzed provides a means to generate map realizations and include a metric of uncertainty at this scale and for meaningful aggregates of 1-km cells (e.g., Bailey’s ecosections).

Task 2b. Develop web-based data mapping & access software.

Software to create, manage, and employ these realizations was developed in Task 2b so that the data are accurately represented and can facilitate cogent analysis by end users. The online data access tool provides the ability to generate multiple alternative plausible realizations of the map, user-specified, where the realizations are drawn from the parametric empirical distributions from Task 1.

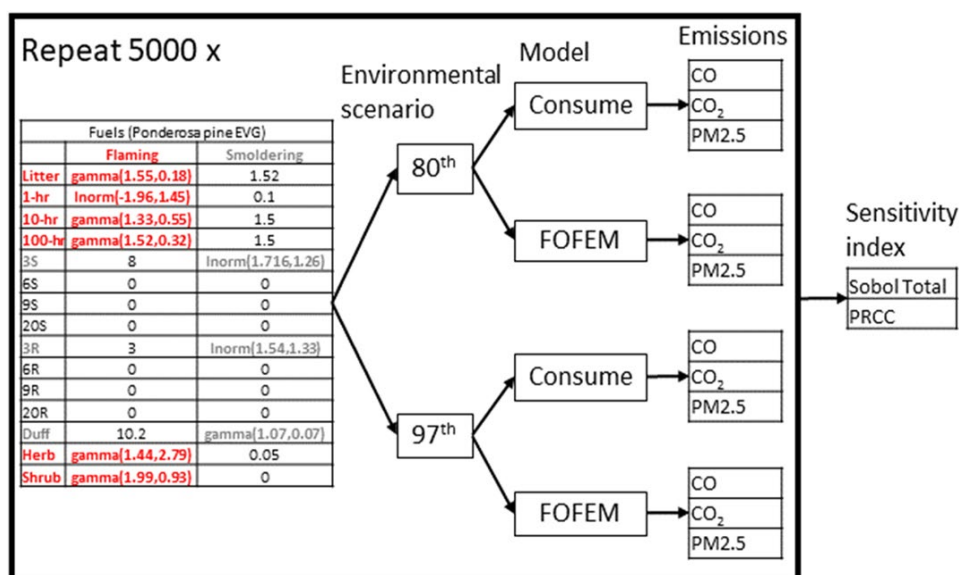


Figure 3. Modeling setup to test the results of using variable input loadings on emissions with two models (Consume and FOFEM) and two environmental scenarios.

Task 3. Assessing sensitivity of emission estimates to fuels

The focus of Task 3 was an analysis of the sensitivity of emissions estimates to variation in fuel-loading inputs for major vegetation types in the US based on the fuel-loading distributions produced and validated under Task 1. For the sensitivity analysis we selected representative fuelbeds, and for each fuelbed conducted a sensitivity analysis by sampling fuel loadings simultaneously from the distributions estimated in Task 1. Two models were employed for the analysis with two environmental scenarios (**Figure 3**). Effects of fuel loading on emissions prediction were assessed for three common air pollutants: PM_{2.5}, CO₂ and CO. For sensitivity analysis, we only considered either the flaming or smoldering phase emissions, whereas we calculated total emissions (flaming and smoldering) for our analysis of how variability propagated to emissions. From the set of sampled fuel loadings and environmental inputs we used each model to estimate fuel consumption and emissions for each fuel loading combination in the input file, for each environmental scenario (80th and 97th percentiles). These were then used in the sensitivity and uncertainty analyses, which are described in Kennedy et al. (in press).

Results & Discussion

The project provides data and tools relevant to the JFSP Smoke Science Plan. The completed work could not have been developed without the previous commitment of resources to field data collection, such as data collected for the USFS Natural Fuels Photo Series and the field campaigns used in the validation exercise. A key project that provided an emissions modeling assessment is the JFSP project 08-1-6-10, the Smoke Emissions Model Intercomparison Project (SEMIP) SEMIP project. Additional previously funded relevant activities were: (1) USFS funding for development and support of the BlueSky framework (N. Larkin, lead); (2) National Aeronautics and Space Administration (NASA) grants to develop the Wildland Fire Emissions Information System (WFEIS) and data (N. French, lead), including the 1-km MODIS-enhanced fuelbed map (McKenzie et al. 2012); (3) USFS funds for development of the FCCS fuelbeds and original FCCS fuelbed map (McKenzie et al. 2007).

Task 1a:

The results of Task 1a were published in a journal manuscript: Prichard et al. (2019). The resulting database (French et al. 2020) contains records for 134 of the total 198 LANDFIRE EVT groups. A total of 68 EVT groups had sufficient entries to estimate at least one fitted distribution of a fuel type. Based on broad physiognomic or land use category, the largest percentage of land area in the United States is classified as forest and woodland (32%) followed by shrublands (19%), agriculture (17%) and non-vegetated pixels (16%). However, the percentage of EVT groups with sufficient record counts for distribution fitting is over-represented by forest and woodland EVT groups (70%) with only 22% and 13% of shrubland and grassland EVT groups represented by at least one fitted distribution. Of the forest and woodland EVT groups there was higher representation of coniferous forests (78%) than broadleaf forests (68%) and mixed forests (63%) for the fitted distributions. Mapped locations of records within the database reveal much higher record availability in forested regions of the US and fewer records for non-forested regions, including much of the central US (**Figure 4**).

For common forest types in the continental US, total aboveground biomass distributions are best represented by a gamma distribution (with nearly no zero values). Observed values range from near 0 to near 500 Mg/ha, with variability depending on EVT group. Median tree total aboveground biomass is comparable for sample mixed hardwood sites, ranging from 71 Mg/ha in eastern floodplain forests to just above 120 Mg/ha in yellow birch and sugar maple (YB-SM) forests and high standard deviations and coefficients of variation. Tree biomass ranges from 0-500 Mg/ha for conifer forests with highest median (Q2) biomass value in Douglas-fir/ponderosa pine/lodgepole pine (DF-PP-LP) forests (108 Mg/ha) compared to 75 Mg/ha for the other forest types.

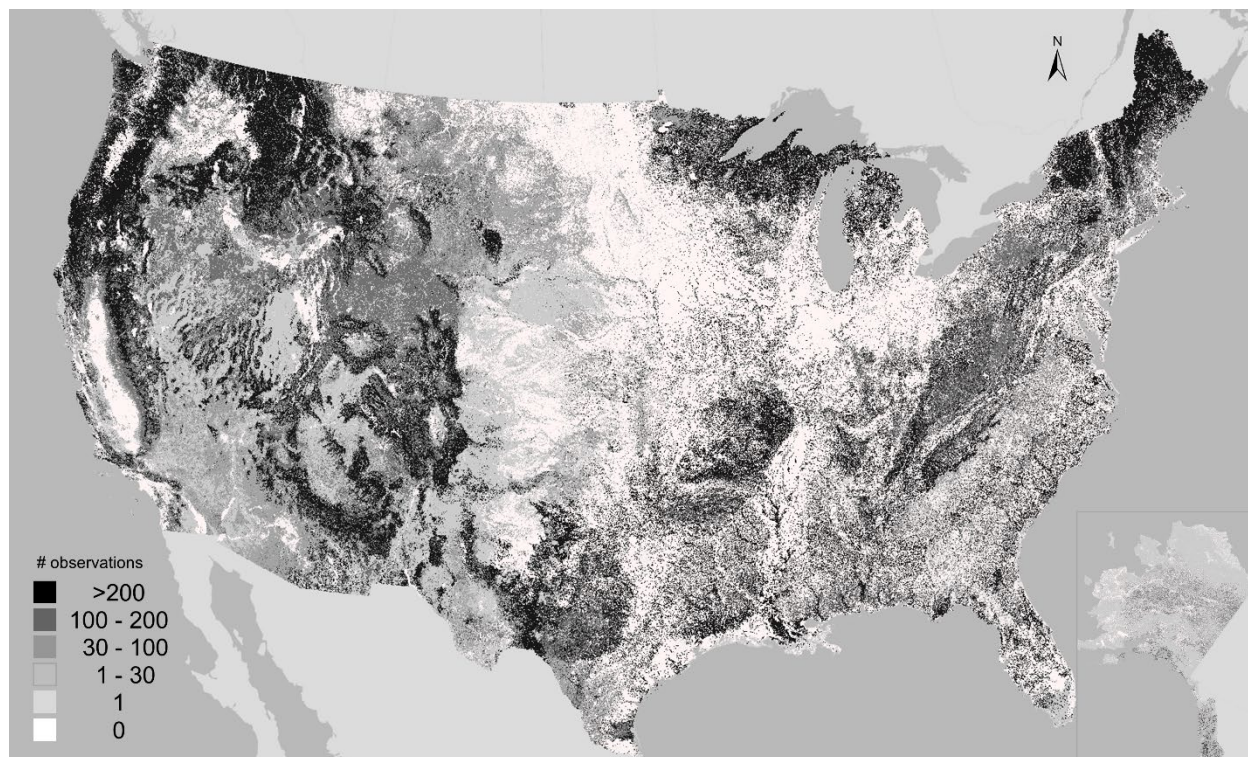


Figure 4. Mapped locations of fuel loading records grouped by number of observations in the conterminous US and Alaska.

Biomass of CWD is particularly variable across records and contributes to high coefficients of variation in distribution estimates. For example, in the 3 sample mixed hardwood forest distributions (**Figure 5**), CWD ranges from 0-50 Mg/ha, and the proportion of zero values is 5.6% in YB-SM distributions, 14% in beech-maple-basswood forests and nearly half of all records for eastern floodplain forests (47%). Median CWD biomass values are quite similar across all mixed hardwood sites as are the shapes of the distributions. In the three conifer forest distributions highlighted here (**Figure 6**), CWD ranges from 0 to nearly 150 Mg/ha, and the proportion of records with a zero value ranges from 8 to 21%. Median CWD is greatest in DF-

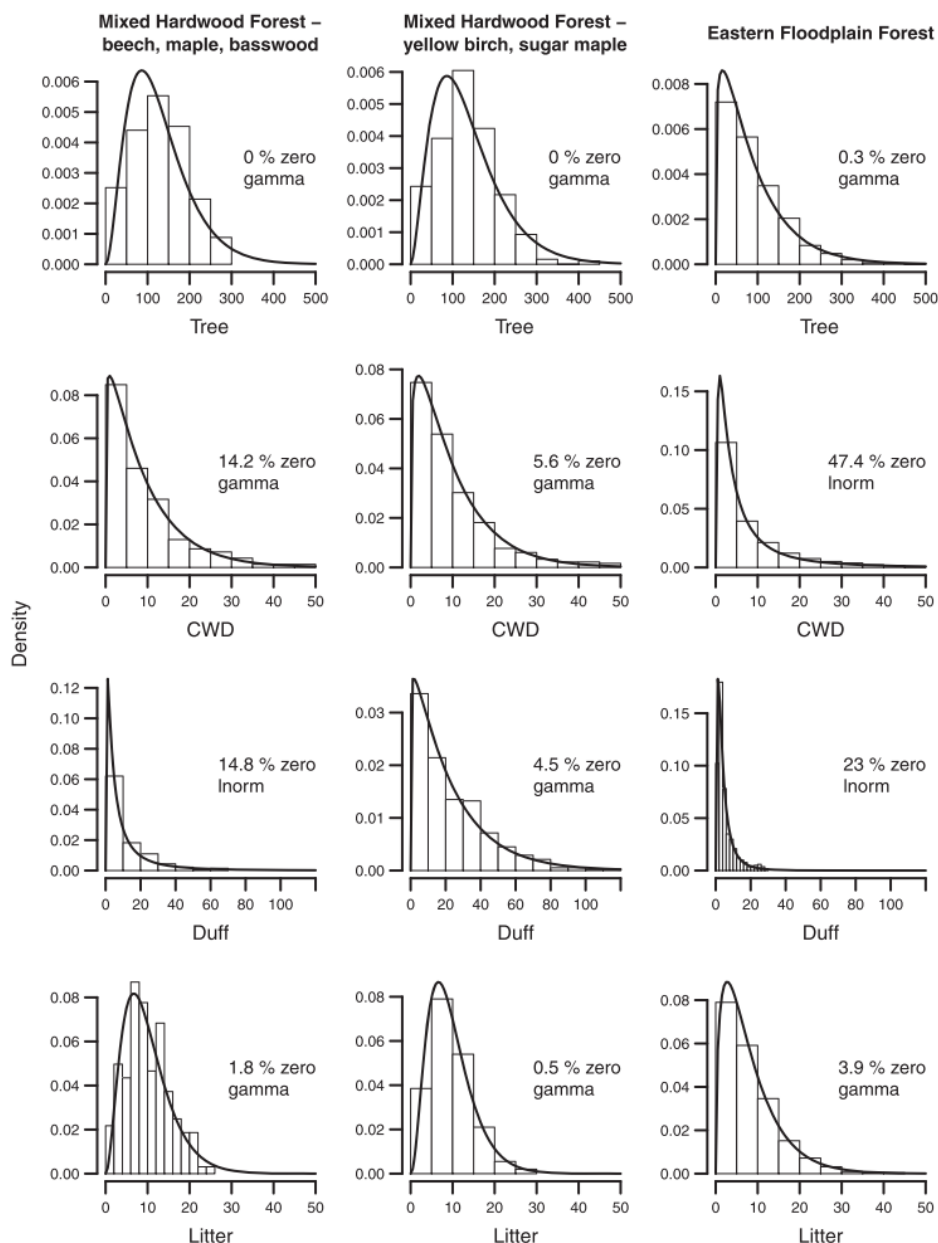


Figure 5. Empirical (histogram) and estimated density function (solid line) for biomass distributions (Mg/ha) for aboveground trees (Tree), coarse woody debris (CWD), and organic soil layers (Duff and Litter) of three sample eastern mixed hardwood.

PP-LP forests and lowest in peat forests. In each case, standard deviations meet or exceed estimated median values.

Duff biomass also has relatively high variability, and records have a relatively low proportion of zero values (4.4 to 7.3%) compared to CWD. Presence of duff is more variable in the 3 sample mixed hardwood forests than conifer forests with the proportion of records without duff ranging from 4.5 to 23%. Median duff biomass ranges from 3 to 17 Mg/ha in mixed hardwood EVT groups, and standard deviations either exceed or are close to the estimated median value. Duff biomass ranges widely from 0 to 250 Mg/ha in peatland forests and 0 to >100 Mg/ha in the other sample conifer forests. Median duff biomass is markedly higher in peatland forests (59 Mg/ha) compared to the other conifer forests (11-15 Mg/ha), and as with CWD, standard deviations are high.

Litter is consistently present across the 6 forest types with less than 5% of records with zero values in the database records. Median values are markedly similar in eastern hardwood forests

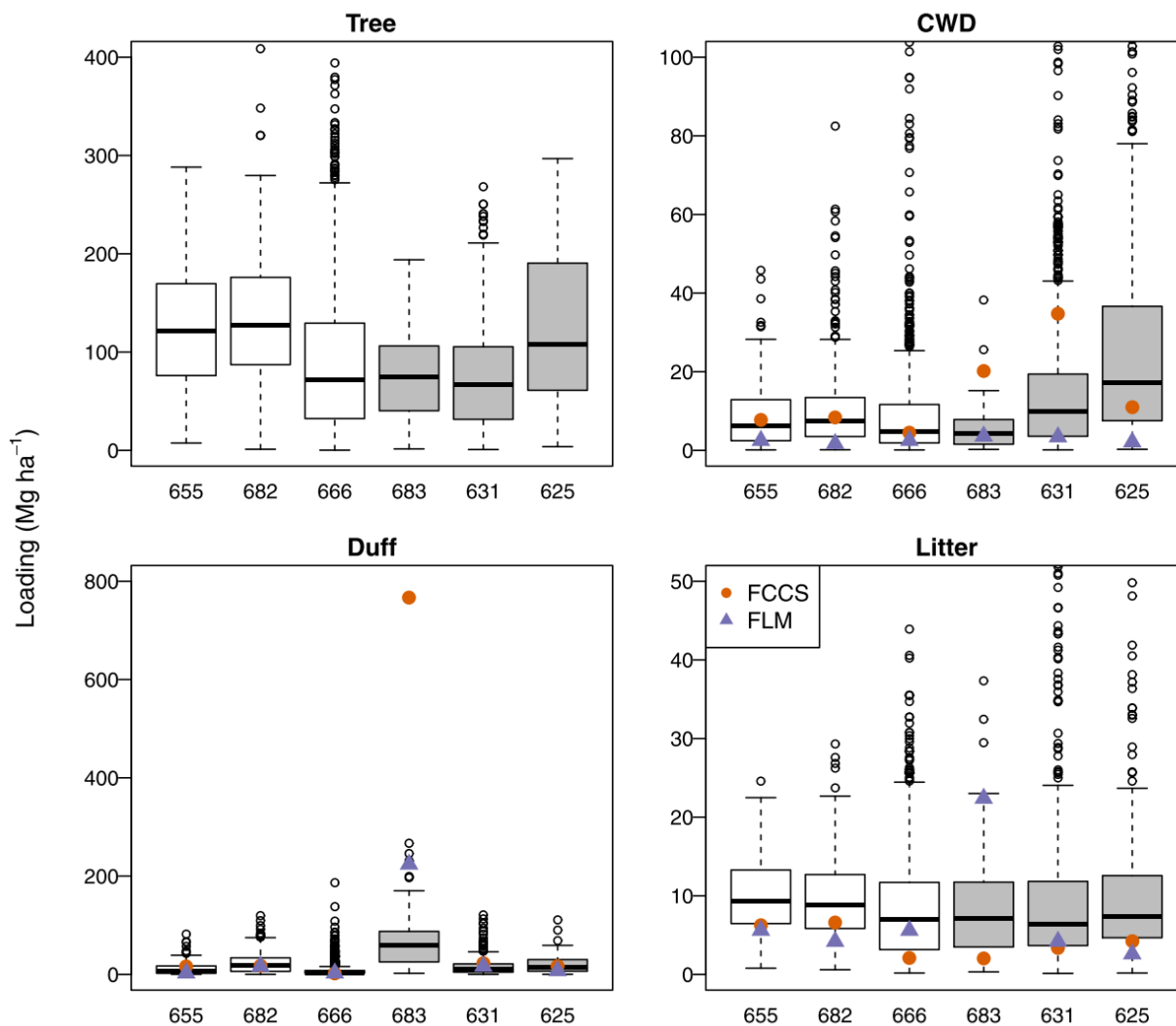


Figure 6. Box plot comparison fuel loading ranges by Existing Vegetation Type (EVT) group. White boxes are hardwood forests, grey boxes conifer forests. For some fuel categories, distributions are very similar (e.g., trees and litter), and for others the

(7-9 Mg/ha), with moderate to high coefficients of variation. In mixed conifer forests, median values are comparable (6 -7 Mg/ha) and have slightly higher CV than eastern hardwood forests.

Because biomass and carbon are most commonly mapped using crosswalks between a vegetation classification and assigned values, we chose to classify biomass observations by vegetation type, using the LANDFIRE EVT Group layer. However, the observed variability is so high within EVT groups that it suggests that an even broader grouping variable by biophysical setting and physiognomic type might be warranted. Based on this finding, we are planning to add a broader classification to the database that will contribute to coarser scale biomass mapping. Database development also revealed substantial bias in data collection toward forest types vs. non-forest types. Given that forests have been intensively measured for timber resources and other forest-management goals, this is not particularly surprising. However, because of the potential importance of these datasets for informing uncertainty in carbon mapping and emissions inventories, the data gaps revealed in this study justify field-based fuel characterization in non-forest vegetation types and inform future sampling.

Even with substantial data gaps identified in this study, the fuel loading dataset should be immediately useful for applications including carbon accounting, fire hazard assessments, and emissions inventories.

1. By using distributions of fuel loading for a vegetation type rather than a point-based map estimate, a credible interval of emissions estimates for carbon accounting can be generated. The ability to calculate uncertainty bounds on model predictions provides users with a plausible range of model outputs rather than a single point estimate.
2. The distributions of fuel loading for major vegetation types can also be used to evaluate potential errors in point estimates given in current map products. Mapped values can be assessed by comparing them to distribution estimates to determine if the mapped values are representative of known EVT distributions.
3. Providing distribution fits by major fuel type can also help inform sensitivity and uncertainty analysis of fuels as inputs for evaluating specific management objectives. For example, we can use the distribution estimates to understand how uncertainty in fuel loadings propagates to uncertainty in wildfire emissions.

Task 1b:

For task 1b validation we used dataset from the Savannah River Site (SRS) and the Sagebrush Steppe Treatment Evaluation Project (SageSTEP). These projects have data representing a range of EVT Groups representative of the southeast and western ecological regions. To compare fuel loading between the validation data and the database, the strata of the validation dataset was crosswalked to the strata in the database and assigned the appropriate EVT Group. EVT Groups were assigned based on the dominant species and geography of the individual plot. Results show comparable probability distribution characteristics between the validation data and NAWFD (**Figure 7**).

Task 2:

The development of the NAWFD on-line system fulfilled Task 2b: *Develop web-based data mapping & access software*, and provides a means for database users to complete Task 2a: *Develop ensemble maps of fuel loadings based fuel loading distributions*. The system is a web-based mapping application (<https://fuels.mtri.org/>) with the following capabilities:

- Visualization and access to fuel loading maps with pixels representing mean, standard deviation, quartiles, minimum, maximum, and number of observations for 30 fuel strata drawn from the distributions produced under Task 1.

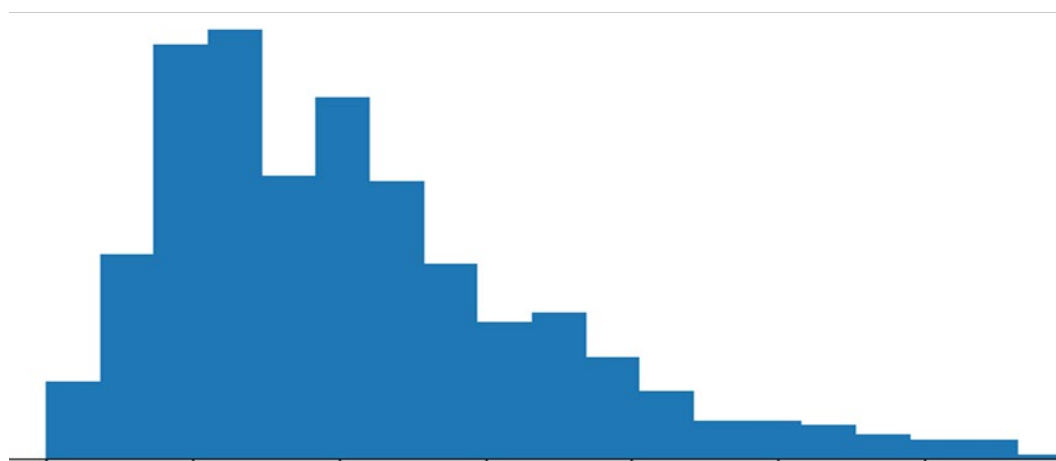
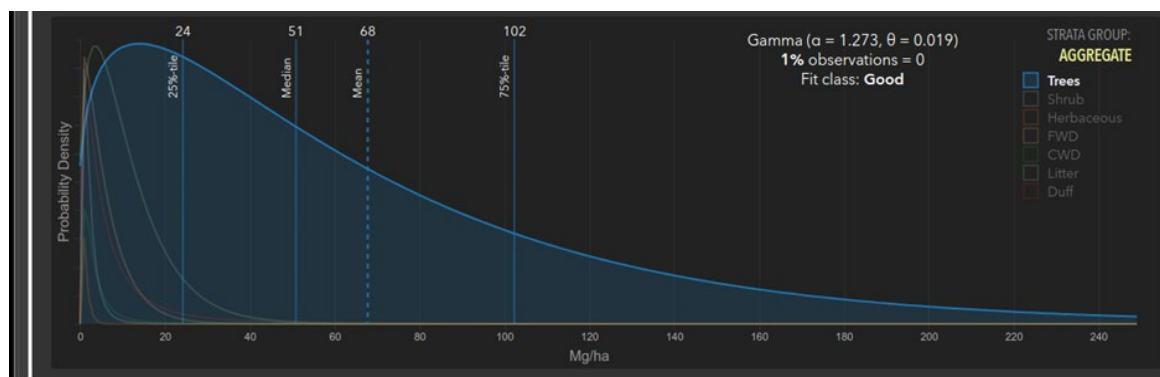


Figure 7. NAWFD probability distribution (above) compared to SRS validation data histogram (below) for EVT group #677 “Longleaf Pine Woodland” tree loading.

- Ability to download stochastically-generated realizations (“ensemble” runs) of fuel-loading maps for inclusion in emissions modeling, as described in Task 2a.
- A matrix graphic showing fuel loading for fuel strata by EVT group fuelbed. The matrix is sortable with optional statistics including summary statistics and number of observations.
- Graphic pages for each EVT group fuelbed showing probability density functions, summary statistics by strata, a coverage map, and a data sources list.
- Data APIs for retrieving geospatial data layers, summary statistics, or probability distribution samples via URL request.

The database and system were presented in the webinar hosted by the Alaska Fire Science Consortium on December 3, 2019 (<https://www.frames.gov/event/551613>). Use of the LANDFIRE EVT groups allows the data to be presented as a map based on LANDFIRE products. The visualization system allows viewing the data in tabular format or as a map (**Figure 8**). The matrix view allows the user to compare and sort fuelbeds and strata by different loading statistics. The map view provides a way for the user to query by pixel or polygon and download static or stochastically-defined loading data.

Additionally, the system allows visualization of statistics and fuels loading distribution functions fitted to each strata (**Figure 9**). References from where the data were collected is available for each fuelbed. Also available on the web site are documentation for the APIs that can be used to download geospatial data, get density function samples, and retrieve summary statistics.

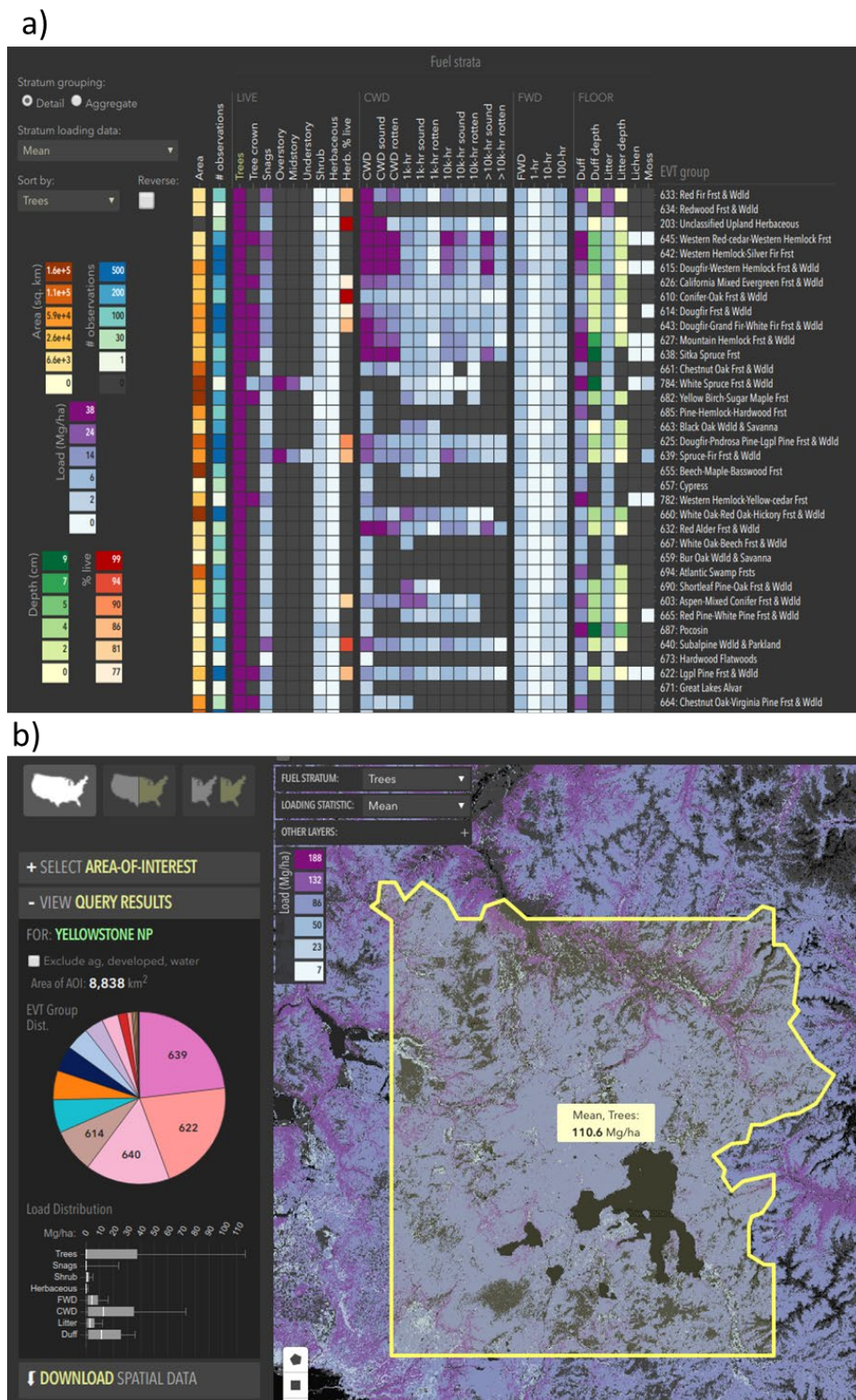




Figure 9. NAWFD Fuelbed Viewer example allowing users to view summary statistics and the probability density functions fitted to each strata by fuelbed.

Task 3:

An analysis was completed to assess the impact of fuel loading variability on emissions. This analysis was recently accepted for publication by the International Journal of Wildland Fire (Kennedy et al. *in press*). Our goal was to evaluate the uncertainty in emissions predictions and identify which fuel layers contribute to sensitivity in emissions.

A primary lesson from the NAWFD was that we do not have sufficient coverage of measured fuels in the USA to quantify, and thereby control for, spatial and temporal variability in fuel loading. Even with the extensive observations of fuel loading that were compiled in the NAWFD, many EVGs lacked enough observations to quantify distributions. Those EVGs that had sufficient observations were confined to distributions for a relatively coarse vegetation classification. Given this reality, associated uncertainty in emissions that are based on fuel loading distributions is quite high.

In this analysis, we used the same sample forest EVGs as in Prichard et al. (2019) to evaluate sources of uncertainty in carbon dioxide, carbon monoxide and PM_{2.5} emissions estimation using two common operational models, Consume and FOFEM. We found that flaming phase emissions were generally most sensitive to litter loading followed by fine wood (10-hr and 100-hr loading). Smoldering phase emissions were most sensitive to coarse wood and duff loadings. However, due to differences in how Consume and FOFEM model consumption, sensitivity to fuel loading inputs across comparative environmental scenarios.

The analysis indicated two ways by which uncertainty in predicted pollutant emissions due to variability in fuel loading inputs can be reduced: First with direct measurement of pre- and post-fire fuels, and second is to increase the measurements of fuel loading across vegetation types and within vegetation types that have little available data. With enough data from different site conditions and vegetation types, and a rigorous analysis of uncertainty (e.g. Prichard et al. 2019), emissions models can be applied more confidently in areas where fires have not occurred. The results of this uncertainty and sensitivity analysis indicate steps that can be taken to reduce uncertainty in emissions estimates.

1. Invest in additional biomass measurements across variable vegetation types, with a focus on those vegetation groups most common and typically fire-affected that are not well represented in the database. Contribute these measurements to the NAWFD. Within the more heterogeneous of these groups more sampling may be needed, especially in types with deep duff layers, which are important predictors of smoldering combustion.
2. For local fire and smoke management, dedicate resources to measuring litter biomass and smoldering fuels, including CWD and duff in areas expected to be affected by wildland fire emissions.
3. Perform full model assessments of Consume and FOFEM, including validation and sensitivity analysis, to characterize uncertainty in model structure.
4. Develop methods to integrate new information on variable fuel loadings into operational fuel classification maps and emissions models, rather than relying on generalized information and broad assumptions about fuel loadings. When that is not feasible, integrate an error metric into the model so the variability of fuels can be accounted for in an uncertainty assessment.

More details on the emissions analysis and sensitivity testing can be found in Kennedy et al. (*in press*).

Conclusions and Implications for Management and Future Research

Development of the North American Wildland Fuels Database (NAWFD), the database access system (<https://fuels.mtri.org/>), the fuel loading distributions (Prichard et al. 2019), and completion of a sensitivity analysis to assess fuel loading variability on emissions uncertainty (Kennedy et al. *in press*) are the outcomes of this study. NAWFD was developed to enable best practices for modeling national- and regional-scale fire emissions by incorporating uncertainty into fuels estimates used in smoke emissions modeling. This work will allow emissions modeling systems to assess emissions more completely by including a quantitative way to take into account the inherent uncertainty in fuels when calculating emissions and associated error metrics. We expect the data to be relatively easy to access by modelers for emissions modeling. We also expect that fire and smoke managers will benefit from the ability to more accurately quantitative uncertainty in smoke emissions.

While these uses may take some time to infuse into current emissions modeling and smoke management practices, an immediate use of the has been to identify gaps in fuel loading measurements (see Prichard et al. 2019). A focus on filling these gaps by collecting relevant field data in underrepresented types will provide more certainty in emissions modeling in regions where these gaps exist. Our studies suggest the follow steps to reduce uncertainty in emissions:

1. Invest in additional biomass measurements, particularly for common fuel types that are not well-represented in the database. This is especially needed in types with deep duff layers, which are important predictors of smoldering combustion.

2. For local fire and smoke management, dedicate resources to measure litter biomass and smoldering fuels, including CWD and duff in areas expected to be affected by either wild or prescribed burning.
3. Perform assessments of emissions models to understand the sources of uncertainty that are due to model structure and their magnitudes relative to uncertainties in the input data.
4. Integrate fuel loading distributions into assessments for emissions inventories, rather than relying on generalized information and broad assumptions. Where distributions are lacking, integrate an error metric into the model so the variability of fuels can be accounted for in an uncertainty assessment.

The NAWFD has been developed to be a “living” database (**Figure 10**); as new data are added, they can be integrated into the database to allow for efficient data analysis. New forms of fuel loading quantification, such as airborne and terrestrial scanning LiDAR, are also anticipated, and the database structure should allow for inclusion of metrics derived from these technologies. We feel the NAWFD and the work done for this project with the database is an important start to having a regimented methodology for fuel loading quantification that is accessible to anyone who needs to use the data. Visit the NAWFD web page (<https://fuels.mtri.org/>) for more information on how fuel loading data can be contributed to the database.

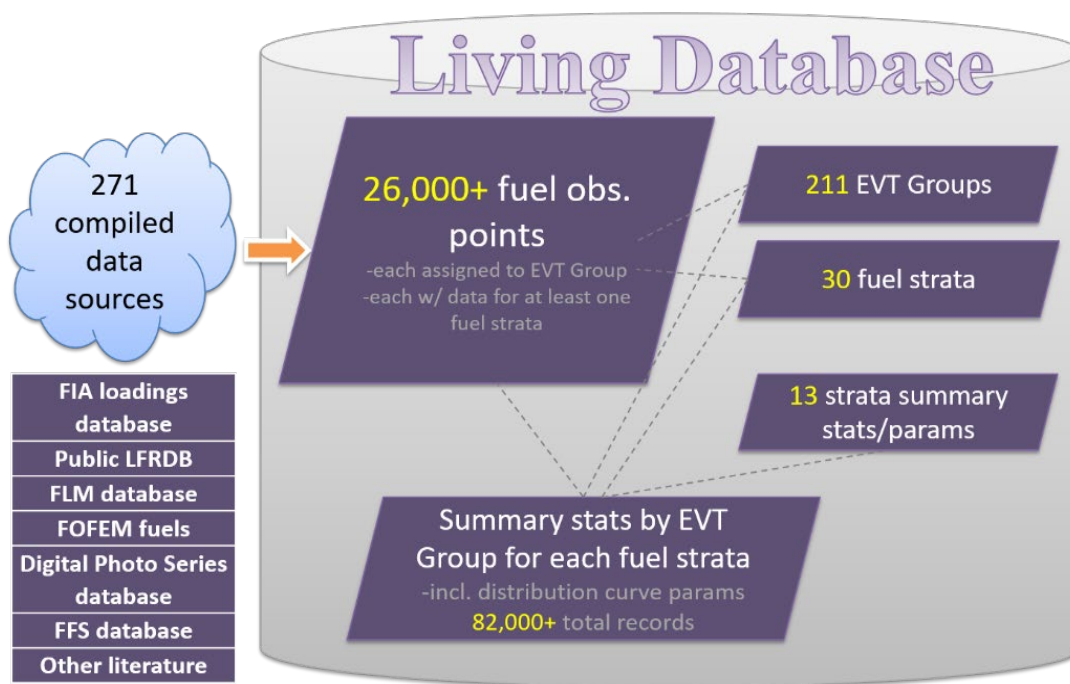


Figure 10: Content of the NAWFD and overview of data sources.

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Appendix A: Key Personnel

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Appendix B: Completed Scientific Publications and Science Delivery Products

Publications:

- Prichard, S.J., Kennedy, M.C., Andreu, A.G., Eagle, P.C. and French, N.H. 2019. Next-generation biomass mapping for regional emissions and carbon inventories: incorporating uncertainty in wildland fuel characterization. *Journal of Geophysical Research – Biogeosciences*. doi: 10.1029/2019JG005083
- Kennedy, M.C., Prichard, S.J., McKenzie, D. and French, N.K. *In press*. How do sources of uncertainty in combustible biomass propagate to wildfire emissions? *International Journal of Wildland Fire*. doi: 10.1071/WF19160

Data product:

North American Wildland Fuel Database: <https://fuels.mtri.org>

Webinar and Presentations:

- French, N.H.F., Prichard, S.J., and Kennedy, M.C. 2019. Webinar “The North American Wildland Fuels Database (NAWFD): Improved Information on Fuel Loading for Fire and Smoke Modeling in Research and Operations.” Hosted by the Alaska Fire Science Consortium. Dec 3, 2019. <https://vimeo.com/377389577>
- French, N.H.F. Prichard, S.J., et al. 2019. “Advancing fuel loading estimates for next-generation mapping, regional smoke management, emissions inventories and air-quality models: Development of the North American Wildland Fuels Database”. Presented at the 6th Fire behavior and Fuels Conference, April/May 2019, Albuquerque, NM, USA.
- French, N.H.F. et al. 2018. “Improving fuel characterization useful for wildland fire emissions and smoke modeling” Poster presented at ForestSAT. October 2018, College Park, MD, USA.
- French, N.H.F., et al. 2017. “Improving Fuel Characterization and Maps useful for Emissions and Smoke Modeling” Presented at Opportunities to Apply Remote Sensing in Boreal/Arctic Wildfire Management and Science, April 2017, Fairbanks, AK, USA.
- French, N.H.F. et al. 2016. “Developing the next generation of fuel loading data useful for emissions modeling” Presented at the 2nd International Smoke Symposium, November 2016, Long Beach, CA, USA.
- Prichard, S., French, N. et al. 2016 “Mapping fuels for regional smoke management and emissions inventories” Presented at the IAWF 5th International Fire Behavior and Fuels Conference, April 2016. Portland, OR, USA.