PHASE 1 OF THE SMOKE AND EMISSIONS MODEL INTERCOMPARISON PROJECT (SEMIP): TEST CASES, METHODS, AND ANALYSIS RESULTS

USFS PNW GENERAL TECHNICAL REPORT

INTERNAL REVIEW DRAFT

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EXECUTIVE SUMMARY

The scientific community has created many datasets and models that can be used to estimate fire emissions and downwind smoke pollutant concentrations from wild and prescribed fires. To estimate emission and/or smoke impacts, several of these models and datasets must be linked into a chain, consisting of fire location information, available fuel loading, fraction of fuel consumed, consumption rate over time, emission factors, plume height, and dispersion/plume chemistry. Land managers, air quality managers, regulators, and practitioners rely upon these estimates to make decisions about planned burning, air quality forecasting, and regulation. These decisions are critical to forest management and the protection of public health. Despite the need for accurate smoke emissions information, there is little science that can provide guidance on which models and datasets are best suited for various conditions; there has been little understanding of which models in a long modeling chain are the biggest sensitivity "knobs"; and there is no framework for determining where the biggest scientific weaknesses and greatest uncertainties lie nor where the model strengths are best suited.

The Smoke and Emissions Model Intercomparison Project, Phase 1 (SEMIP) provides an expandable and open framework for organizing and addressing critical issues in fire emissions modeling. The SEMIP structure includes:

1) Definition of a sequence of *model steps* necessary to estimate emissions and downwind concentrations;
2) Definition of *model output levels* in between model steps where different model pathways can be directly compared;
3) Creation of a variety of *test cases* that are designed to assess one or more models by comparing model output to other model output and/or to observed data; and
4) Development of infrastructure for supporting model and data intercomparison, including a *data warehouse* and *metadata catalog*.

The development of this structure provides many benefits:

- Systematic intercomparisons between models and between model chains can be performed;
- Systematic comparisons between models and observations can be performed;
- Areas most critically in need of research can be identified;
- Areas of greatest uncertainty can be identified;
- New models and datasets can be tested against existing models and established benchmarks for specific test cases;
- New test cases can be added as evaluation data become available or key needs are identified; and
- Researchers can contribute their own models, datasets, and test cases.

In addition to laying out the structure needed to organize future research, numerous analyses were identified and performed, spanning six model output levels across nine test cases. Key findings are detailed in this document, but a few of the most important findings are:

- The lack of fire occurrence information for small fires, especially prescribed burns, is a major source of uncertainty for emissions inventories.
- Fuels maps, even modern high-resolution maps, differ significantly and systemically; as such they are a major source of uncertainty even in national annual emissions totals.
- Consumption models are critically dependent on fuel moisture, but these dependencies differ from model to model.
- Emissions factors in many models have lagged behind scientific literature, and the differences can be large, especially for lesser emitted species.
- Assumed diurnal time profiles for wildfires interact with meteorological conditions in significant and non-linear ways, making modeled smoke impacts sensitive to the time profile assumptions.
- Plume rise calculations show regional, fire size, and fire type systematic biases when compared with satellite measures of plume height; coupled with the sensitivity of modeled smoke impacts to these parameters, plume height becomes the most significant challenge to correctly predicting air quality impacts.

Based on the key findings of SEMIP, we propose several recommendations for the smoke modeling and management communities:

- SEMIP, or something like SEMIP, should be continued into the future, in order to establish and maintain baseline comparison Test Cases and to ensure that standard comparisons between models and model validations needed by users of the models are done on a regular basis.
- An invested structure (e.g., a small scientific oversight board) should be chartered to respond to requests and comments from the larger scientific and management communities. This group would maintain and approve the Test Cases to be maintained and provide advice to the JFSP Board on critical needs.
- New datasets and test cases should be curated and available to the scientific community.
- Continued model comparisons and evaluations should be conducted, especially when new models or model versions are created. Some targetable funding might be useful to enable the most urgent comparisons, with larger efforts done through the standard JFSP RFA process.
- New observation campaigns should be created with Test Case development and targeted towards areas of limited understanding. While the area of limited understanding may be at one modeling step, such as plume rise, data would have to be collected at all modeling steps for the Test Case to be complete.

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ABSTRACT

Managers, regulators, and others often need information on the emissions from wildland fire and their expected smoke impacts. In order to create this information, combinations of models are utilized. The modeling steps used follow a logical progression from fire activity through emissions and dispersion. In general, several models and/or datasets are available for each modeling step, and the resulting number of combinations that can be created to produce fire emissions or smoke impacts is large. Researchers, managers, and policy makers need information on how different model choices affect the resulting output, and guidance on what choices to make in selecting the models to use. Baseline comparisons are needed between available models that highlight how they intercompare, and, where possible, how their results compare with observations. As new models and methods are developed, standard protocols and comparison metrics are needed that allow these new systems to be understood in light of previous models and methods.

The Smoke and Emissions Model Intercomparison Project (SEMIP) was designed to facilitate such comparisons. In Phase 1, SEMIP:

- examined the needs for fire emissions and smoke impact modeling;
- determined what data were available to help evaluate such models;
- identified a number of test cases that can serve as baseline comparisons between existing models and standard comparisons for new models;
- created a data warehouse and data sharing structure to help facilitate future comparisons; and
- performed a number of analyses to examine existing models.

This report documents the activities of Phase 1 of SEMIP conducted October 1, 2008, through September 30, 2012, including key results and findings, summary conclusions by modeling step, and future possibilities.

1. INTRODUCTION

This General Technical Report (GTR) documents the methods, analysis techniques, and key findings of Phase 1 of the Smoke and Emissions Model Intercomparison Project (SEMIP). Phase 1 of SEMIP (hereafter SEMIP) was funded by the Joint Fire Science Program (Project #08-1-6-10) and completed September 30, 2012.

1.1 Goals of SEMIP

SEMIP was designed to be an open community standard that could serve as an on-going testbed for understanding how fire emissions and smoke impacts can be modeled. The design of the project was based on previous and existing model intercomparison projects (MIP). Similar to these projects, datasets and test cases were defined with the intention of future use (beyond the lifetime of the project) for testing and analyses of new theories or models. The intention is to allow for a robust history of model results, and to provide a testbed platform to facilitate understanding how models evolve through time.

As such, SEMIP was structured as an open standard for comparing smoke and emissions models both against each other and, where available, against observations. By identifying a number of specific "test cases" for model intercomparisons / evaluations, these test cases could become baselines for analyzing future model improvements (e.g., as new models are created and/or existing models are updated). Additionally, SEMIP: Phase 1 was designed to perform a number of the most needed analyses on currently available models to help benchmark current model performance.

1.2 Goals of This Report

The goals of this general technical report are twofold:

1. Provide a summary of SEMIP activities, results, and findings done under Phase 1; and
2. Provide a reference of SEMIP structure and analysis techniques that can serve as a blueprint for follow-on comparisons.

The Final Report to the JFSP (http://firescience.gov) includes a high-level summary of the key findings of SEMIP. This report herein provides additional detail in support of these findings, as well as comprehensive documentation on the test cases, analysis procedures, and methods used for SEMIP. Combined with the attached Appendices and the data available within companion data storage and display websites developed as part of SEMIP, this report is intended to allow other researchers to:

- Access the analyses and results done as part of SEMIP;
- Reproduce the analyses and results done as part of SEMIP; and
- Add to the analyses done as part of SEMIP using additional and/or updated models as they become available.

As such, this document is divided into sections on the background of SEMIP (Section 2), the structure of SEMIP – including a list of identified points of model comparisons that can be done and an initial test cases – (Section 3), the results found in the SEMIP analyses (Section 4), and conclusions and suggestions for future development of SEMIP (Section 5). Appendices provide reference details, including the structure of the SEMIP data warehouse (Appendix A), what analyses were done for each test case (Appendix B), a list of models and datasets used (Appendix C), and the specific analyses done for each output level (Appendix D).

2. BACKGROUND

2.1 How Fire Emissions and Smoke Impacts Are Modeled

In order to model smoke impacts there is a logical progression of questions that occur:

- Where are the fires and how big are they?
- How much fuel is there?
- How much fuel was consumed?
- When and how was it consumed?
- What emissions and heat were produced?
- How high up into the atmosphere did the smoke go?

- Where did the smoke get transported?
- How was the smoke altered during transport?

Each of these can properly be thought of as a distinct modeling step (shown here with a shorthand name in parentheses):

- Basic fire information detection / reporting (FIRE INFO)
- Fuels (FUELS)
- Fuel consumption (TOTAL CONSUMPTION)
- Time profile of consumption (TIME PROFILE)
- Emissions speciation of the consumption (EMISSIONS)
- Plume rise injection heights of the fire (PLUME RISE)
- Smoke trajectories and dispersion (DISPERSION)
- Chemical alterations of the constituents within the smoke plume as the smoke combines and reacts with other chemical species in the atmosphere (CHEMISTRY)

Note: we utilize the shorthand name (shown in parentheses above) for simplicity throughout the rest of the document. Figure 1 shows the modeling steps and output levels and identified and examined in SEMIP.

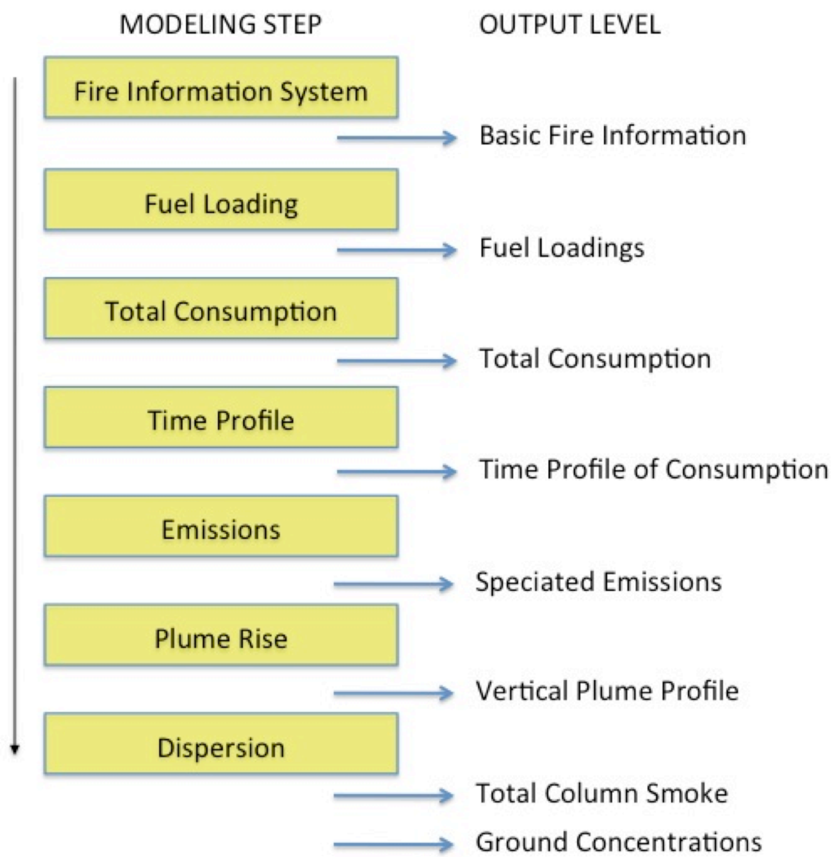


Figure 1. Modeling chain including modeling steps and output levels identified and examined by SEMIP. See Section 3.1 for more details. Note that the TIME PROFILE modeling step can also be placed after EMISSIONS, in which case the output level becomes the Time Profile of Emissions. Plume chemistry was not treated by SEMIP:Phase 1.

Each modeling step is distinct in that it transforms the available data by either creating a new orthogonal axis of information (e.g., a list of chemical species for the EMISSIONS step) or combining existing information into new summary information for further processing (e.g., combining all of the various fuel components into a list of total amount consumed by fire phase for the CONSUMPTION step, thereby eliminating the need for further use of the fuel component data). Naturally, not all steps are required and the steps followed depend on the specific information desired. For example, most fire emissions inventories do not contain any information past the EMISSIONS step.

For each modeling step, many models have been developed that can compute an answer. Some models are *dynamically* based using physics, chemistry, or other first principles, while others are *empirically* based through statistical fits of observations. The types of models are generally more distinct in theory than in practice – often dynamic models require tuning using the same types of data used to develop empirical models, while empirical models utilize first principles in identifying the types of statistical relationships to be derived.

The result of having multiple choices for each modeling step is that the number of combinations of models to form a given *modeling pathway* increases geometrically as more modeling steps are included. This explosion of possibilities dramatically increases the potential number of different answers available by merely changing which models are selected as the modeling pathway. As a result, there may be multiple ways to achieve the same (or similar) final answer (such as fire emissions or smoke concentrations) with very different inherent assumptions and intermediate values (such as total consumption or plume rise).

Not every model/modeling system conforms to the above pattern exactly. For example, a specific consumption model may model the full time rate of consumption first, and then create total consumption values. However, we list total consumption here because it is *conceptually* simpler, and *practically* easier to verify (e.g., from pre- and post-burn plots). Additionally, some models specifically skip steps by creating statistical relationships that bridge multiple listed steps. For example, fire emissions are computed from satellite-detected radiance measures through fire radiative power (FRP) relationships. These relationships directly associate observed "brightness" of the fire with emissions without the need to compute a specific consumption value.

SEMIP addresses these types of issues by allowing for models to be compared when and where they have outputs (see analyses by output level in Appendix D).

2.2 Use Needs for Fire Emissions and Smoke Impact Modeling

There is a wide range of use needs (applications) for fire emissions and smoke impact modeling in research, management, and policy (Figure 2). Use needs can vary on their required timeliness (is this in support of real-time decision making or a retrospective analysis), the relative aggregation (e.g., national annual totals) or temporal and regional localization (e.g., location-specific hourly data) of the required output, and the ultimate type of data required, which is usually related to the purpose of the modeling (e.g., fire emissions reporting vs. public health smoke impact modeling). At two extremes of the use cases are:

- Historical analysis of national, annual emissions totals (e.g., for greenhouse gas accounting); and
- Real-time forecasting of smoke impacts on sensitive receptors (e.g., hospitals, airports, roads).

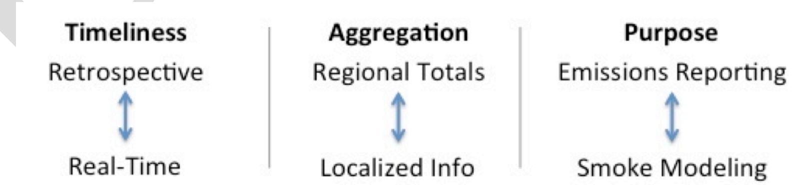


Figure 2. Range of usage needs for fire emissions and smoke impact modeling information.

2.3 The Need for Organized Data / Test Cases

Creating fire emissions and/or smoke impacts requires combining models together into a modeling pathway. If observation data are only available for the output of a long modeling chain (e.g., for ground $PM_{2.5}$ [particulate matter with diameter less than 2.5 microns] concentrations) or for a limited number of applications, it may be difficult to determine if the individual models are producing the correct results. It is possible to obtain the "right" answer from a modeling chain for the "wrong" reasons because of large but compensating errors within the chain (such as significantly overpredicting total consumption but then using an emissions factor that is too low, which results in compensation for error in total consumption). A hypothetical example is shown in Figure 3. In addition, each model within the pathway can have numerous settings; the more parameters available for adjustment the greater the amount of observational data required to evaluate the total modeling pathway. Having data from intermediate points (e.g., fire information, fuel loadings, total consumption, plume injection height) can help pin down where the modeling chain is most problematic and where it is physically correct and producing good results.

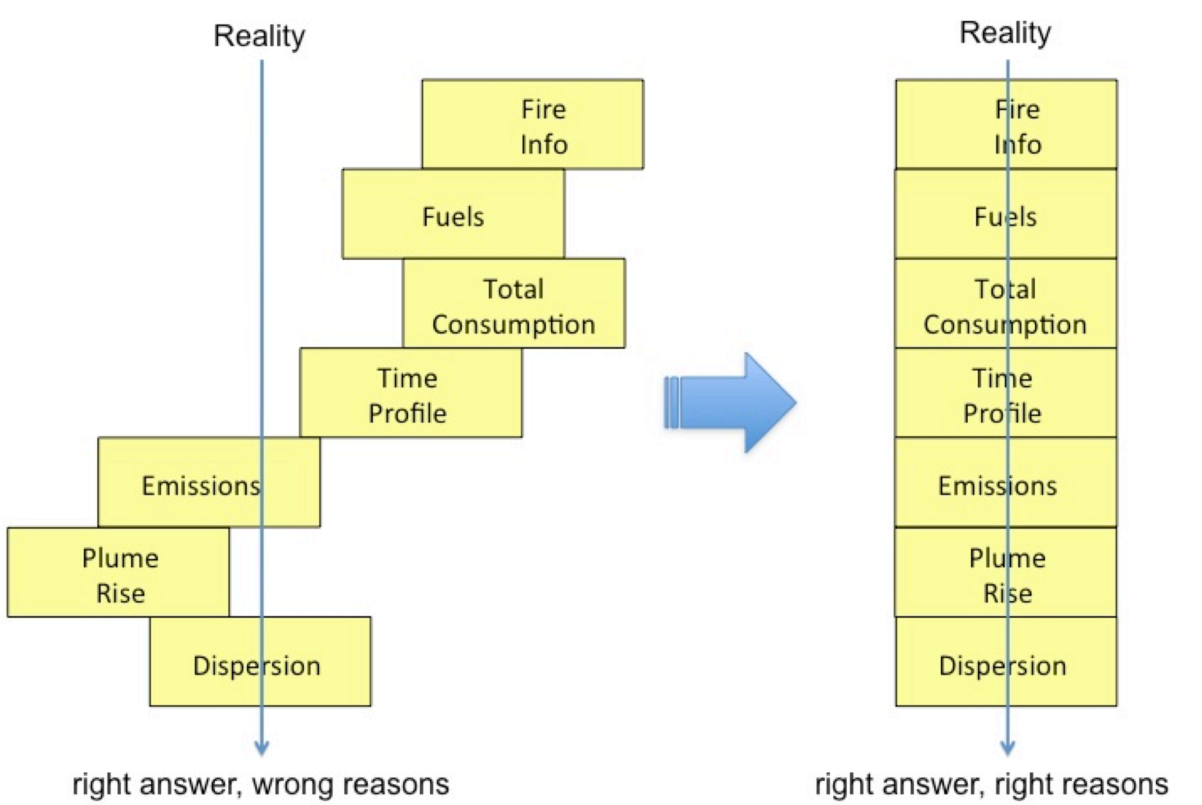


Figure 3. Schematic of propagation of errors within a modeling chain. Even if the final result of the modeling chain is correct, it is possible for it to have been achieved through compensating errors. Ensuring that the entire modeling chain is accurate requires analysis of multiple output levels.

Test cases, where a significant amount of data is collected and many models are run for the same set of input parameters, provide a mechanism both for looking in depth at the full modeling chain and for providing understandable comparisons between models and even between versions of the same model. It is best to build test cases where a critical mass of observational data is available in order to promote not only model-to-model intercomparisons but also model evaluations at as many output levels as possible.

To find such collections of data, at the beginning of the SEMIP project (Spring 2009), we conducted a review of past JFSP funded projects based on information available at the time on the JFSP website (http://firescience.gov). Although it was necessarily a subjective assessment based on limited data, we identified 142 completed projects that seemed likely to have data of value to SEMIP. The projects were estimated to break down as:

- 22 have information related to Meteorology
- 53 have information related to Basic Fire Information
- 106 have information related to Fuel Loading
- 61 have information related to Total Consumption
- 14 have information related to Time Rate of Consumption
- 13 have information related to Emissions
- 9 have information related to Plume Rise
- 12 have information related to Dispersion

Projects were randomly selected and investigated further. Only a small minority had readily accessible data. Additionally, based on the descriptions available to us, only in a very limited number of cases was there a full suite of data representing the full fire emissions / smoke impact modeling chain collected from a single fire event.

Since the inception of SEMIP, the JFSP has significantly altered the manner in which new projects are expected to handle data collected or created for the project, possibly due in part to the above analysis. Recent requests for applications (RFAs) have required proposal submissions to identify both how and where data, including metadata, collected and/or created for the project will be archived. Suggested archives have been given, such as the U.S. Forest Service Data Archive. This effort, if successful, will undoubtedly make data access issues such as those faced by SEMIP significantly easier. Questions remain as to whether such archives will accept and aggregate together not only information directly collected and/or created for the project but also ancillary data necessary to run and evaluate models, some of which can be quite large (e.g., meteorological model output from the National Weather Service, or satellite remotely sensed data).

Also potentially making data identification and access easier are improved web interfaces and search forms, such as the one created for the SEMIP Data Warehouse (Appendix A). These types of customized search forms allow users to more easily specify the type of information of interest in terms commonly used by the research community – data types (e.g., basic fire information vs. plume injection heights), data location (e.g., regions of the country, coverage within that region, and time period of interest), type of observational platform (e.g., plot data vs. remotely sensed data), and specific included data (e.g., species lists vs. aggregate fuel loadings, or specific chemical species).

3. SEMIP STRUCTURE

SEMIP is organized around a number of *test cases* that are designed to allow for models and modeling pathways to be intercompared and evaluated across a number of *output levels*, so that uncertainties and errors within each *modeling step* can be evaluated.

3.1 Modeling Steps and Output Levels

SEMIP identifies a number of *modeling steps* within the fire emissions / smoke impacts modeling chain (see Section 2 and Figure 1). [It is important to note here that we distinguish between TOTAL CONSUMPTION and TIME PROFILE OF CONSUMPTION. We do this for three reasons: (1) because TIME PROFILE is not always need (for example in computing total emissions); (2) because different information is available to evaluate each; and (3) because the Time Profile of Consumption output adds a new temporal dimension to the model output data.] For each modeling step, SEMIP identifies specific *output levels* where model output can be compared and evaluated (Figure 1 and Appendix D). The goal of each step's analysis is to quantify the model-to-model variations and the model-to-observation differences at that output level for both scientific and user guidance, and to best describe the variability as it relates to modeling steps downstream in the modeling chain.

For each output level, SEMIP defines a number of specific outputs and *analyses* that are common to most models and can provide a useful basis for comparison (see Section 3.2 and Appendix D). Additional outputs available for only some subset of the models are also done; these allow for a more detailed analysis where those outputs are available. The outputs and analyses do not describe the complete set of data that can be produced by the models used in SEMIP. For example, not all models can produce total consumption by fire phase (flaming, smoldering, residual). Therefore, SEMIP defines the Total Consumption output analyses first in terms of overall total fire consumption (across all phases), and only secondarily by phase where available.

3.2 Test Cases

Test cases were selected to represent real-world applications of the various models contained within SEMIP. In aggregate, these test cases ideally cover the majority of real-world use cases. In practice, the test cases are necessarily more limited, largely due to restrictions of data availability. The identified test cases are a cross between available data and the need to represent as wide an array of usage needs as possible. As the science and usage needs evolve, or as additional data become available, additional test cases will be necessary to fully represent the needs of the scientific and management communities. The current test cases can only provide an initial, imperfect attempt to capture as much of the needed initial analyses as possible.

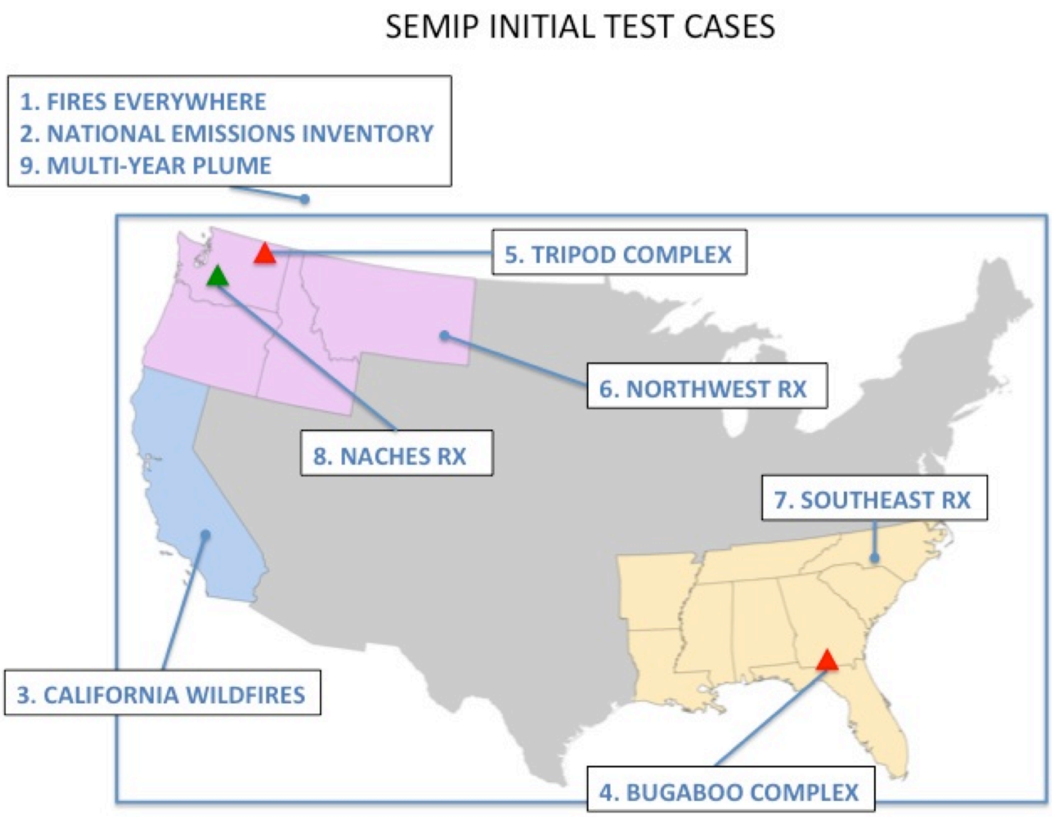


Figure 4. Map showing the locations of the SEMIP:Phase 1 test cases. Locations of individual fires (Tripod Complex, Bugaboo Complex, and Naches Prescribed Fire) are shown with triangles. The area of interest is shaded for the regional cases (California Wildfires, Northwest Prescribed Fires, Southeast Prescribed Fires). As discussed in the text, the test cases cannot fully represent the usage needs for fire emissions and smoke impact modeling. Additional test cases will be needed as data become available.

3.2.1 Test Case Structure

Each test case consists of:

- A set of fires;
- A set of modeling steps to examine;
- Collected datasets and model inputs that can be used to initialize and run the models, thereby allowing all of the models involved to be directly compared based on equal inputs; and
- Where possible, observational datasets that can be used to evaluate the models, thereby distinguishing not only model differences but also model performance.

In addition to the above, each test case has specific identified outputs and analyses that were determined to be the principal focus of the test case, at least initially.

3.2.2 List of Test Cases

An initial set of test cases were identified for SEMIP: Phase 1 (Figure 4). The initial test cases were designed to try to maximize their applicability across the country and across typical model uses. Effort has been made to include cases across temporal and spatial scales, and to maximize the amount of observational data that can be used for evaluation at each modeling step. Test cases were created by examining data availability, model intercomparison needs, spatial and temporal scales, and model use applicability. In general, data availability was the most critical component in identifying a viable test case.

As SEMIP progressed, this list of test cases evolved. A new multi-year test case (#9) was added to allow for the examination of plume rise, and the two regional prescribed fire test cases were put on hold for Phase 1 in order emphasize work on other test cases. The lists here and in Figure 4 represent the current set of test cases. Should SEMIP continue, additional test cases will continue to be added, and test cases put on hold and deemed no longer of value can be dropped.

The current list of SEMIP test cases are:

1. **Fires Everywhere:** for examining fuels, consumption, and emissions everywhere throughout CONUS;
2. **2008 National Emissions Inventory:** for examining the fuels, consumption, and emissions as they create a multi-use emissions inventory (test case currently limited to large fires);
3. **2007/2008 California Wildfires:** for examining emissions and smoke in a large regional fire setting;
4. **2007 Bugaboo Complex:** for examining emissions and smoke in a large wildfire complex in the southeast that has deep organic consumption;
5. **2006 Tripod Complex:** for examining emissions and smoke in a large wildfire complex in the west;
6. **Northwest Prescribed Burning:** for examining emissions and smoke in a large regional prescribed burn setting in the west; [deprecated for Phase 1]
7. **Southeast Prescribed Burning:** for examining emissions and smoke in a large regional prescribed burn setting in the west; [deprecated for Phase 1]
8. **2009 Naches Prescribed Burn:** for examining emissions and smoke from a single prescribed fire; and
9. **Multi-year Plume Case:** for examining plume rise as seen by satellites across multiple years.

For details on each test case see Appendix B.

3.2.3 Spatial and Temporal Scales of the Test Cases

Test cases were chosen to represent a variety of temporal and spatial scales. In addition, within each test case there are a number of scales—information associated with each fire contained within the test case, and likely for each day of each fire, if not for each hour, as well as spatial coverage of not only the fire itself, but also its plume's vertical structure and horizontal dispersion. Due to the diverse scaling, the test cases are classified by their maximum spatial and temporal scales. This is defined by the horizontal scale of the smoke impacts (dispersion) and the temporal scale of the collected fires within the test case. In Figure 5 the test cases are plotted on both maximum spatial scale (x) and maximum time scale (y) axes. The Fires Everywhere case uses climatological fuel moisture and winds and so is classified at the "climatology" scale.

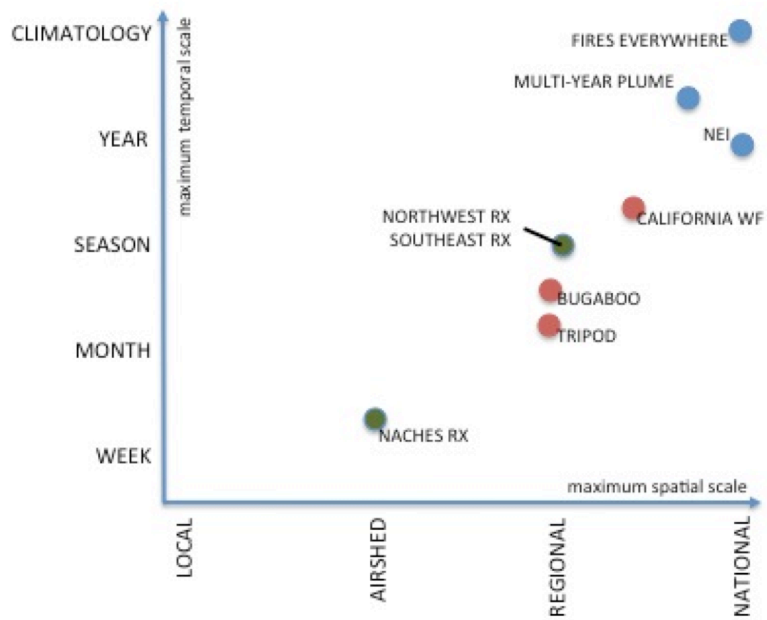


Figure 5. Spatial (x-axis) and temporal (y-axis) scales of the selected test cases.

The maximum scales defined in Figure 5 are only the maximum possible extent over which an analyses statistic could be calculated, but there is nothing to prevent choosing a smaller scale within each test case as needed. For example, a single fire can be extracted from the National Emissions Inventory calculations. The regional prescribed burns cases are shown as not extending down to the local scale because individual prescribed burns do not lend themselves to standard remote sensing and downstream sampling observations because of their usual limited smaller size. It is possible that some of the prescribed burns will be big enough to examine individually, but this is the exception, not the rule. Single prescribed burns, such as Naches 2011, can be analyzed at the local scale where test case standard data are available for the analyses.

For Phase 1, SEMIP examined each test case across its largest spatial and temporal scales, using statistics to aggregate results as described in Appendix D. In many cases there are several spatial ranges used for statistical analyses, for example by region or vegetation type.

3.2.4 Analysis Levels by Test Case and Analyses Performed

The varying test cases lend themselves to analyses at different modeling steps (Figure 6). Potential analyses were identified for as wide a range of modeling steps as possible. In addition, the selection of test cases was based in part on the potential for analyses over a wide range of output levels.

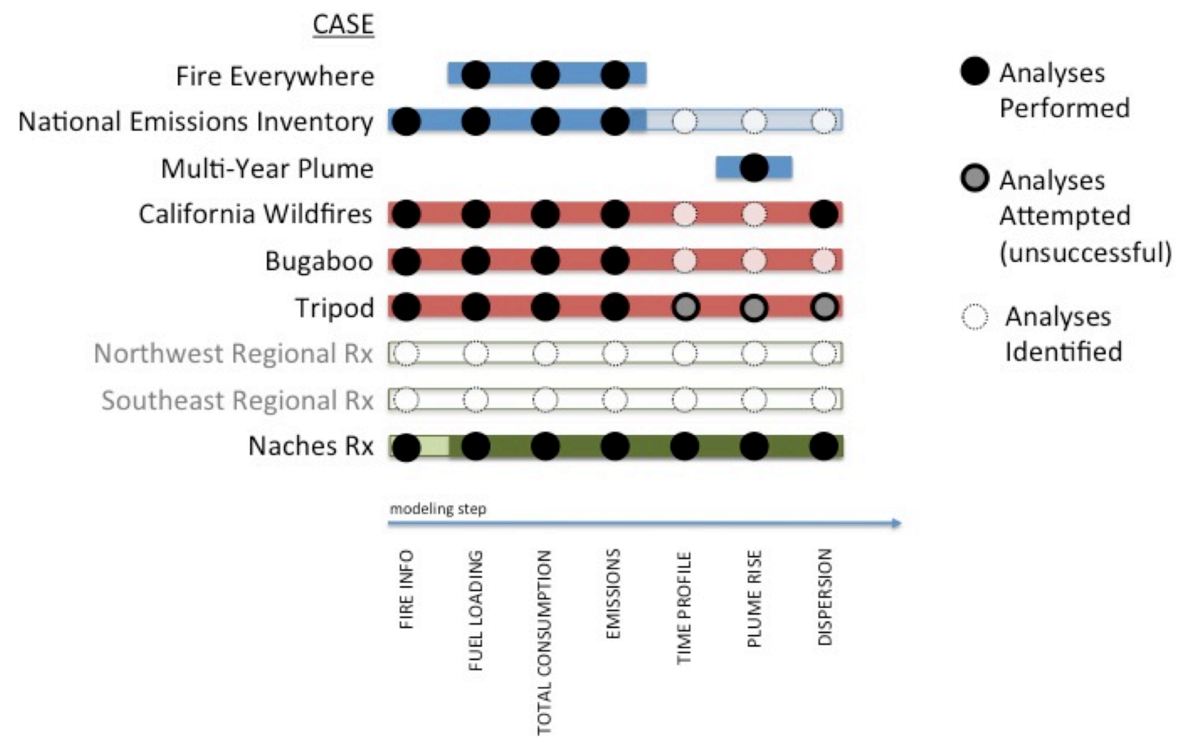


Figure 6. Analyses identified, performed, and attempted by modeling step and test case. Where analyses related to a modeling step were completed, black circles are shown. Unsuccessful analyses are shown with a grey circle. Where potential analyses were identified but not performed as part of SEMIP:Phase 1, a grey line and dashed grey circle are shown. Solid color bars for a test case indicate the original intention of the test case; lighter colored bars show how test cases were extended into additional modeling steps.

The Phase 1 of SEMIP did not cover all modeling steps for each test case. For Phase 1, analyses were initially chosen to give a wide array of information across all modeling steps. Later analyses were selected to cover issues identified through earlier analyses results. As SEMIP progressed, analyses on fire information, fuels information, total consumption, and total emissions were emphasized, due to findings that analysis of the rest of the modeling chain

(TIME PROFILE, PLUME RISE, and DISPERSION) is heavily data limited and strongly affected by uncertainties in the calculations leading to emissions. Thus, SEMIP: Phase 1 necessarily provides a more complete picture of the fire emissions modeling chain than of the emissions to smoke impact modeling chain. See Sections 4 and 5 for more information.

Note: not all analyses performed by SEMIP were ultimately successful. Attempts to use ground concentration data measured during the Tripod Complex to infer information on the diurnal time profile of emissions and the plume injection height profile of the smoke were unsuccessful in that they did not provide statistically meaningful results. This inverse methodology is likely to be more successful where additional observations or simpler fire dynamics / meteorology / terrain are available.

3.2.5 Adding New Test Cases

Assuming that the basic structure of SEMIP continues past Phase 1, it is expected that additional test cases will be added to complement these initial cases, and that revisions to the test case list will need to occur periodically as new datasets become available and our scientific modeling capabilities progress. It is proposed (see Section 5) that this be done by a scientific advisory committee empowered by the JFSP.

An example of a current JFSP project with the potential to create a useful test case is the RX-CADRE field measurement campaign set to commence in Fall 2012 at Elgin Air Force Base, Florida. By creating a dense set of measurements across a wide swath of model output levels, RX-CADRE may prove to be a valuable testbed for fire emissions and smoke impact modeling chains in the future. Other recent sub-canopy smoke and other projects funded by the JFSP may also provide useful multi-output level observational data with which to create a test case.

3.2.6 Limitations of the Test Cases and the Need for Additional Analyses

In performing analyses for SEMIP it was determined that not all of the modeling steps were conducive to being analyzed by specific test cases alone. Specifically, FIRE INFORMATION, EMISSIONS, and PLUME RISE all had difficulty with the test case paradigm used in SEMIP as described below.

FIRE INFORMATION is adaptable into the SEMIP test case structure, and, indeed, useful analyses were done using the 2008 National Emissions Inventory test case. The large inhomogeneity of fire information collection and availability; the rapid change in techniques for remotely sensing fire information, including available satellite sensors; and the policy and adoption changes within ground reporting systems require that fire information analyses be done wherever data become available. SEMIP completed a fire information analysis by examining probability of detection from satellite sensors (see Section 4.1.1).

For PLUME RISE, the difficulty is in finding observational data with which to compare the model results. For SEMIP, we have created a specific test case (#9), which is designed simply to allow for a full comparison of plume rise as modeled with any and all satellite observations of wildland fire plumes that were identified over a three-year time period (see Section 4.2.6).

The EMISSIONS modeling step is the most problematic for the test case methodology simply because of the paucity of data available. In examining emissions factors SEMIP primarily adopted a literature review methodology rather than a test case one, looking for all published emissions factors and comparing these numbers. The published emission factors were derived from observations, a subset of these data was used to compare to the empirically derived emission factors from one of the emission models. An intercomparison of two or more emissions models was completed using existing models (i.e., Fires Everywhere) for some test cases (see Section 4.2.5).

4. RESULTS

This section presents key results and highlights of the SEMIP analyses. First, two sensitivity analyses are summarized to show which model steps have the most influence on the overall uncertainties in smoke modeling. We determined that the answer depends on the use case of the model results. Second, we provide a summary of the key results of analyses at each model step. These synthesize multiple analyses across one or more test cases. Additional details on the full range of analyses and findings are provided in the appendices.

4.1 Sensitivity Analyses

The largest sensitivities in fire emissions and smoke modeling depend on the use case the modeling information is being put towards (see Section 2.2).

To illustrate this we examined two cases:

1. Computation of fire emissions national annual totals; and
2. Computation of smoke concentrations from a single fire.

Overall sensitivity for fire emissions totals is dominated by (in descending order):

a. Fuels information (overall fuel loadings and fuel loadings in specific important types, such as canopy fuels and deep organic fuels);
b. Fire information (overall total area burned and area burned by type of fire);
c. Consumption model assumptions (for canopy fuels, deep organic consumption); and
d. Emissions factors for $PM_{2.5}$ and lesser emitted species (e.g., volatile organic compounds (VOCs)).

For smoke concentrations from a single fire, overall sensitivity is dominated by (in descending order):

a. Plume rise (the number of assumed plume heat cores);
b. Time profile (the timing of consumption throughout the day and its relation to the ambient meteorology); and
c. Uncertainties in fire emissions (see above).

Not studied by SEMIP: Phase 1, but known to affect smoke concentrations, are the uncertainties of in-plume chemical processes, transition of these processes with plume age, and the difference between clean-air smoke plume chemistry versus urban-air smoke plume chemistry. Sensitivity studies that include plume chemistry should be included in future work.

4.1.1 Overall Sensitivity for Fire Emissions Totals

2008 National Emissions Inventory – Large Fires Only

To investigate the overall sensitivity of the fire emissions modeling chain to each modeling step, the 2008 NEI test case was used to compute total CONUS wildland fire emissions. Because estimations of fire size are known to vary considerably, only the large fires identified by the Monitoring Trends in Burn Severity (MTBS) fire perimeters (over 1000 acres in the west; over 500 acres in the east) were used (Figure 7). These perimeters are not uniformly distributed, instead being distributed in the areas with the largest burned areas in 2008—California and the southeast.

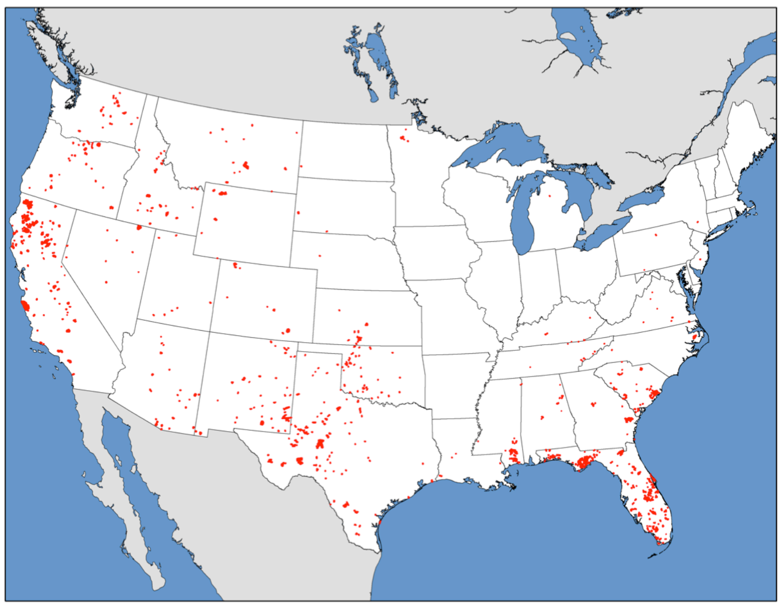


Figure 7. 2008 large fire locations from the MTBS dataset. Adapted from Larkin et al. (2012).

In aggregate, the dominant difference in the pathway to emissions is found within the fuels (Figure 8). For example, LANDFIRE fuels are found to be approximately half of the FCCS v1 and FCCS-LF fuels. This same variation continues for consumption as well, with the differences in fuels overwhelming any difference in consumption models (noted by a 'C' or 'F' within each fuel-color band). The exception is FINN, which despite having similar fuel loading totals to FCCS-LF, has only half the consumption of FCCS-LF > Consume[1] or FCCS-LF > FOFEM. Emissions totals generally follow consumption totals for more abundant smoke components

[1] Note: when describing modeling pathways here we use the convention that Model 1 > Model 2 > Model 3 describes the sequential processing of the data through Model 1 first, then Model 2, then Model 3.

(such as $PM_{2.5}$ shown here), but can vary considerably for trace components. However, even for $PM_{2.5}$, variation between consumption models is seen due to differences in emissions factors and differences in how consumption models partition consumption between flaming and smoldering phases.

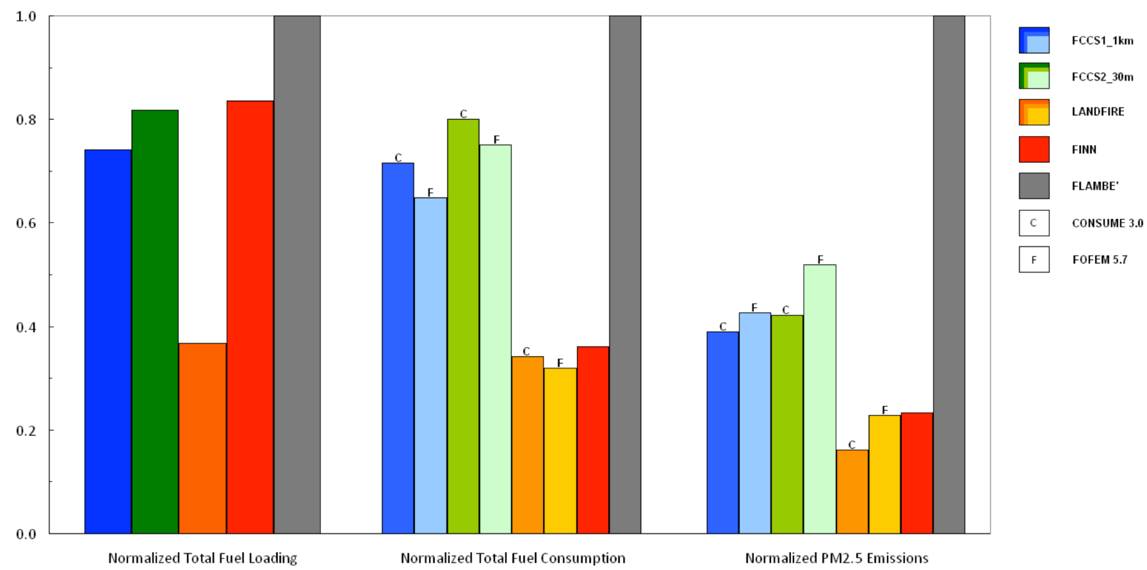


Figure 8. Fuels, consumption, and $PM_{2.5}$ emissions calculations for various modeling pathways. Aggregated for the 2008 large fires shown in Figure 7. Fuels are aggregated for all locations within the MTBS perimeters for FCCS version 1 1-km fuels, FCCS-LF (labeled FCCS2) 30m, LANDFIRE 30-m fuels, and the FINN and FLAMBE fuels datasets. Results are shown normalized to the highest aggregate fuels, total consumption, and $PM_{2.5}$ emissions (FLAMBE in all cases). Adapted from Larkin et al. 2012.

This type of sensitivity to modeling pathway, described above, can be found within the results from the 2008 National Emissions Inventory test case (see Section 4.2.1). Within this test case Fire Information systems were tested to discern the sensitivity of emissions on their reported information. Results show that differences in how fire information systems report burn area, in particular the inclusion/exclusion and/or inability to detect prescribed burns, makes a large difference in overall annualized fire emissions. This influence on emissions is second only to the fuel loading differences found above.

4.1.2 Overall Sensitivity for Smoke Impact Predictions

Naches Prescribed Fire

To examine the overall sensitivity for smoke impact predictions of steps in the modeling chain, we used the Naches Prescribed Fire Test Case as a relatively simple and isolated fire with very high resolution meteorology (1.33-km grid, every 10 min) available. Changes were made artificially to the results of various pieces of the modeling chain, and the effects on the modeled smoke concentrations were examined. Specifically, alterations were made in turn to the fire size, overall fuel loading, overall fuel consumption, overall $PM_{2.5}$ emissions, time profile curves (both time shift and shape of the curve), and plume injection heights.

For many pieces of the chain (fire size, fuels, consumption, and emissions) linear or nearly linear effects were observed (Figure 9, left). This is generally true for both maximum concentration and average concentration within the domain; for both overall fuel loading and overall consumption, modeled concentration changes were near a 1:1 ratio. Metrics showing area of impact above a threshold typically did not follow a simple pattern, but typically showed an overall less than 1:1 ratio.

Plume rise showed significant non-linear, and at times confusing trends (Figure 9, right). In some cases, altering plume rise did not significantly alter the metrics of modeled smoke concentrations, while at other times small shifts in plume rise had strong effects. This appears to be due to the interactions of plume rise, the planetary boundary layer, wind shear, and the terrain near the fire. If plume heights put emissions into a layer of the atmosphere that then is forced close to the ground due to terrain, modeled ground smoke concentrations go up. If plume heights put emissions into a layer of the atmosphere that moves away from the terrain, raising their height above ground level, smoke concentrations go down. The strong non-linearities in plume rise effects makes plume rise a significant issue in any smoke modeling.

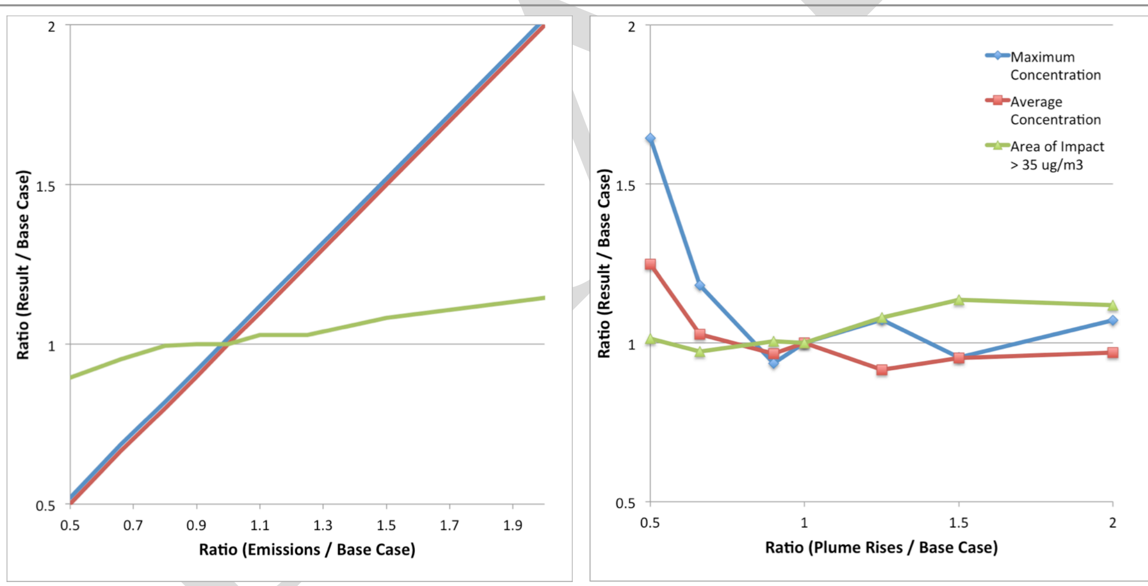


Figure 9. Changes in domain maximum concentration, domain average concentration, and total area of impact > 35ug/m^3 based on altering the amount of $PM_{2.5}$ emitted (left) and plume rise modeled (right). Results shown are for the Naches prescribed fire test case using the WRAP time profile. A value of one indicates no overall change to the metric; a value of two indicates that the changes resulted in a doubling of the overall metric.

Also found to be critical is the time profile of emissions. Small shifts or alterations to the overall shape of the time profile were found to sometimes have significant consequences (see Section 4.2.4 and Figures 18 and 19 for more information).

4.2 Key Results by Modeling Step

Information on the strengths and weaknesses at each modeling step is important to ascertain and understand because each modeling step is affected by the previous steps. We therefore present the results below by model step rather than by test case.

4.2.1 Fire Information

As the first link of the smoke modeling chain, fire information forms the foundation of smoke and emissions modeling. Fire information is defined here as data on the existence, size, location, and timing of burning. Each of these factors impacts downstream model output. For single fire studies on well-observed fires, fire information can be very precise, and it represents only a small fraction of overall modeling uncertainty. For larger scale studies, however, fire information can be one of the largest single sources of uncertainty (see Section 4.1.1).

There exist myriad sources of fire information, both ground-reported and remotely sensed. The eight fire information data sources analyzed in SEMIP fall into four broad categories:

1. Ground Reporting Databases – e.g., Incident Command Summary reports (ICS-209)
2. GIS analysis of helicopter or aircraft overflight data – e.g., GeoMAC perimeters
3. Remote sensing of actively burning fires – e.g., NOAA Hazard Mapping System (HMS)
4. Remote sensing of burn scars – e.g., Monitoring Trends in Burn Severity (MTBS)

We assessed sources of fire information for both single-fire and national-scale test cases. Details are provided in Appendix D.1.

Key Results

Good ground-based reporting (or detailed post-analysis) is the best retrospective resource for individual fires where it is available. Especially for large wildfires, accurate data are often available on the final size, shape, and progression of the fire. Figure 10 shows the Tripod fire as seen by three fire information data sources. The GeoMAC perimeter closely matches the perimeter from the MTBS project, but the area calculated from the Moderate Resolution Imaging Spectroradiometer (MODIS) active fire data is a third larger.

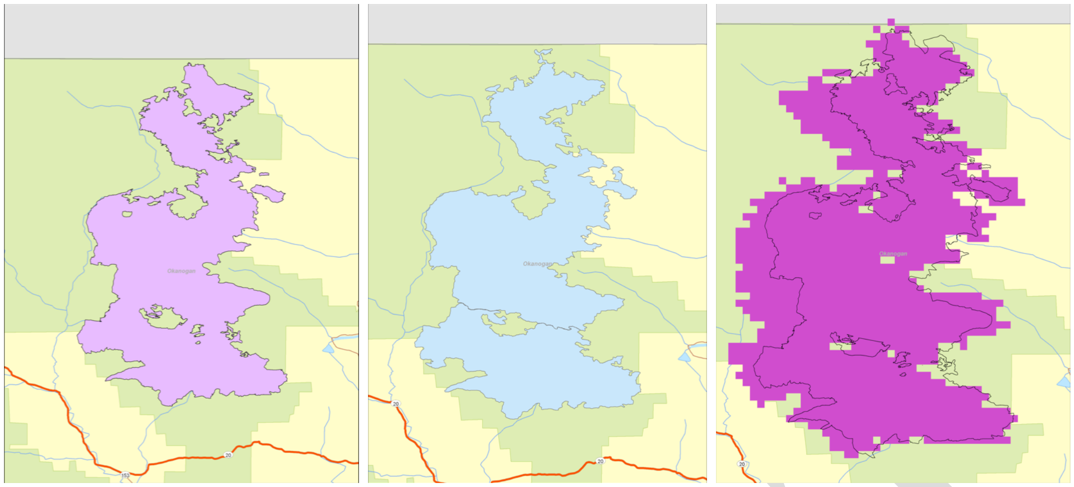


Figure 10. Area burned maps for the Tripod Complex fire from GeoMac (left), MTBS (center), and MODIS active fire detects (right). Adapted from Raffuse et al. 2012.

For smaller fires, it is much less likely that data from ground-based reporting systems or post-analysis are available. This is particularly a concern for quantifying prescribed burning locally and at a national scale. ICS-209 reports are limited predominantly to wildfires and some wildland prescribed burns. MTBS strives to capture all fires greater than 500 acres in the east and 1000 acres in the west (defined as the column of states running from North Dakota to Texas and westward). Thus, until smaller prescribed burns are well reported and information is made available at the national level, remote sensing products provide the best opportunity to estimate the quantity of small fires.

Not all fires are captured by satellites because of cloud cover obscuring the satellite's view, the small size or low intensity of the burn during the satellite overpass timing, the ability of the sensor to detect understory burns, or other factors. The combination of geostationary and polar-orbiting sensors, such as provided by the HMS fire detects, is found to detect more fire activity than polar-orbiting sensors alone. Figure 11 shows the detection rates as a function of fire size for active fire remote sensing products on grass and shrublands. MODIS is the most widely used instrument for developing emissions estimates globally. HMS includes MODIS, but adds other polar-orbiting sensors, geostationary sensors, and human quality control. These curves suggest that emissions estimates based on MODIS active remote sensing may underestimate the number of small fires present on the landscape.

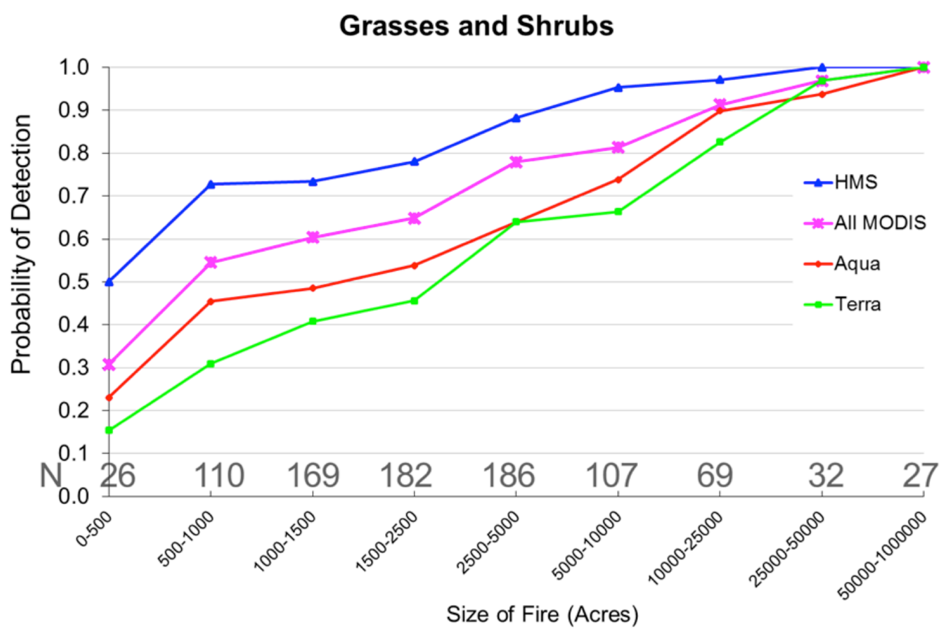


Figure 11. Probability of detection of large grass and shrub fires for active fire remote sensing datasets. Terra and Aqua are the two MODIS platforms. All MODIS includes both Terra and Aqua. HMS includes All MODIS, plus GOES, AVHRR, and human analysis. Adapted from Raffuse et al. 2012.

Despite the large number of fire information data sources available, no single data source captures all fires. In addition, the different data sources have different strengths and weaknesses. For example, while MTBS fire severity maps provide an excellent record on area burned for large fires, they do not include most small fires (less than 1000 acres in the west and 500 acres in the east) and provide no information on the time profile of burning (daily or hourly). Furthermore, MTBS data are not available until at least a year after the burn, which makes them unusable for some applications, such as operational predictive smoke forecasting. In contrast, active remote sensing products, such as HMS, are available in near real time and provide daily information on the location of fires, both large and small. However, the area burned is not provided by active remote sensing products and must be inferred.

There is growing evidence that small fires, especially prescribed burns, make up a substantial portion of the fire occurrence in the United States. For example, the recent Prescribed Fire Use Survey Report developed by the Coalition of Prescribed Fire Councils (Melvin, 2012) reports 20 million acres of prescribed, rangeland, and agricultural burning nationwide in 2011. Contrast this with the 8.7 million acres of wildfire reported by the National Interagency Fire Center's 2011 Annual Report and only 2 million acres of prescribed burning in the same report. This discrepancy is also an issue in databases (e.g., the Global Fire Emissions Database) used in global climate models. These databases rely on satellite-derived fire detections and burn scars and tend to underreport small, low-intensity understory burns. There is a critical need for local prescribed burn reporting to reach the emissions modeling community. Based on the data availability and timeliness considerations, the best approach for national scale applications, such as the National Emissions Inventory, is to combine all data sources that can be acquired, applying methods to merge information where multiple data sources detect the same fire.

Conclusions

While fire information is typically well known for single fire case studies, it remains a major source of uncertainty at regional to global scales. Researchers and model developers who wish to build upon fire information results from SEMIP should consider the following recommendations. Further work intercomparison analyses should be conducted on remotely sensed burn scar products (e.g., Giglio et al., 2010: Roy et al., 2005). Validation work is particularly lacking in assessing the ability to account for prescribed burns and their size. Analysis should be conducted to compare state prescribed burn area estimates against the recent Prescribed Fire Use Survey Report developed by the Coalition of Prescribed Fire Councils (Melvin, 2012). Finally, analysis of modeling pathways using satellite-observed Fire Radiative Power, which combine fire information, fuels, and consumption into a single model step, should also be pursued.

4.2.2 Fuels

Fuels play an essential role in fire emissions and smoke impact modeling. Fuel information as used here is a description of the amount of biomass available to burn. This can be live or dead organic matter in any number of "strata" including on the ground, above-ground, in the canopy, and/or in deep organic layers, as long as consumption of the fuels allows a fire to ignite, sustain, or spread (Keane and Reeves 2012). Fuels are generally associated within a landscape to a fuel type such as open pine forests, closed conifer systems, grasslands, or chaparral. Descriptions of fuels are commonly separated into strata including canopy, snags, stumps, shrubs, grasses, and size classes of sound and rotten fuels (e.g., 1, 10, 100, 1000, 10,000 and 10,000+ hour fuels), litter, and duff. Differences exist between what strata different fuel maps report. Both the general fuel type and the quantities of biomass in individual fuels strata contribute to the type and quantity of fire emissions produced.

Mapping and assessing fuels is a difficult and time consuming process. Generally, fuels maps are available at various spatial resolutions and numbers of strata. Many approaches to mapping fuels exist (Keane et al. 2001); however, it is difficult to assess the accuracy of fuels mapping efforts as fuel loading varies greatly across space and time. Fuels can be estimated indirectly through remote sensing techniques, but this is difficult and problematic. Passive sensors provide spectral information that can be classified to fuel types, but dense canopy cover precludes observation of the understory and the depth of various strata, such as duff, generally cannot be determined. Additionally, detection of some change agents such as thinning can be difficult. Active remote sensing, such as LIDAR, can provide more structural information, but these measurements are typically not available across the landscape. Depending on the methodology used, determination of woody fuel sizes can be difficult. Additionally, fuels are highly variable at multiple scales across landscapes, and fuels that were assessed accurately at one point in time can be changed by a single event, such as a windstorm or wildfire, not reflected in the fuels datasets.

Modern fuel mapping efforts tend to utilize ground plots to create representative fuelbeds, which are then distributed over the landscape via algorithms based on remotely sensed vegetation types. This process introduces potentially large uncertainties into modeling fire emissions and smoke impacts, as fuel quantities can vary by many magnitudes across a landscape, even with the same fuel type (e.g., Larkin et al. 2009).

In addition to issues with distributing fuels across the landscape, fuel map information varies with the purpose of the map. Fuel loading maps can be broken down into three broad categories: fire danger rating maps, fire behavior maps, and fire effects maps. Fire danger rating maps were designed to assess the likelihood a fire will ignite and continue to burn. Fire behavior maps were designed to be used to predict the spread of fire across landscapes. Only fire effects maps were designed specifically to predict, in part, fire emissions. Because of this, the fuel quantities in fire danger maps and fire behavior maps do not specifically reflect actual fuel amounts in the landscape.

Additional uncertainty is introduced to smoke emissions modeling by global scale fuels models utilized in systems such as FINN and FLAMBE. These fuel loading maps are coarse scale assessments of fuels on the ground based on general fuel types such as grasslands, shrublands, conifer forests, and deciduous forest. These coarse scale maps cannot reflect the variability exhibited at the local scale.

In SEMIP, we assessed many different spatial sources of fuel loadings which are described in detail in Appendix D.2. Some key findings will be discussed below.

Many systems exist that provide spatial assessments of fuels useful for modeling smoke emissions. In SEMIP, we compared 9 different fuel loading maps designed for different reasons (see Appendix C for details on the various maps):

- NFDRS - 1 km
- Hardy98 - 1 km
- FCCS v1 - 1 km
- FCCS-LF - 1 km
- FCCS-LF - 30 m
- FLM/LANDFIRE - 30 m
- OkWen Custom FCCS - 25m
- FINN -1 km
- FLAMBE - 30 arc second

Each of these maps was designed for use in fire emissions modeling except the NFDRS, which was created as a fire danger rating tool.

Key Results

Figure 12 shows the ranges in fuel loadings for the Tripod Complex (2006 in Washington State, see Appendix B.4) Figure 12 includes maps produced over a wide range of time periods: the

NFDRS (Burgan et al., 1997; Burgan et al. 1998), Hardy98 (Hardy et al., 1998), FCCS v1 (McKenzie et al., 2007), LANDFIRE FLMs (Lutes et al., 2009), FCCS-LF maps (McKenzie et al. 2012), and the OkWen Custom FCCS map (McKenzie et al. 2007). The older maps (NFDRS, Hardy98, FCCS1) were used in this study to illustrate fuel loading map variability and to discuss how fuel loading mapping evolved over time. These older maps are neither currently supported nor updated and should not be used for future smoke emissions modeling efforts.

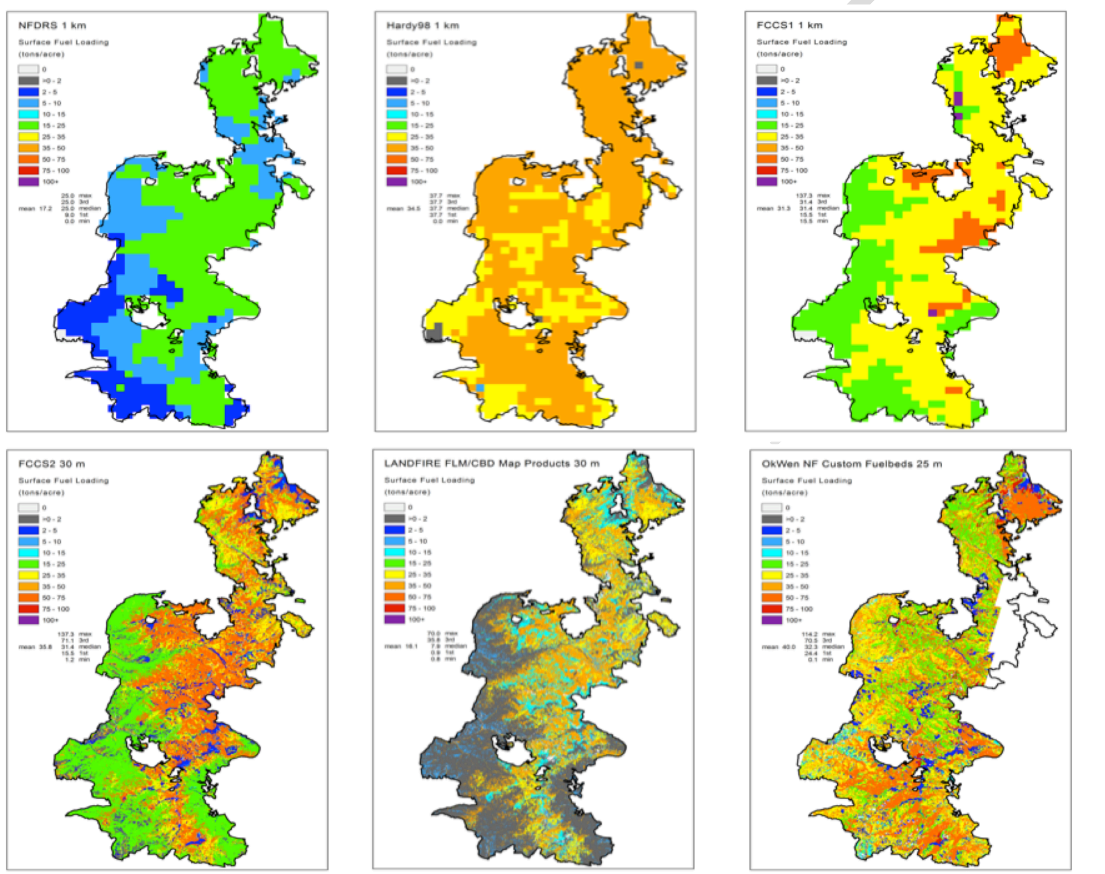


Figure 12. Surface fuel loading variability for the Tripod Fire. Adapted from Drury et al. 2012.

Of the three current fuel loading maps (FCCS-LF, LANDFIRE, OkWen, bottom row Figure 12), the OkWen Custom FCCS map has the highest overall surface fuel loading for the Tripod test case (average 40 tons/acre) followed closely by the FCCS-LF map (average 35 tons/acre), with LANDFIRE FLM maps showing the lowest (average 16 tons/acre). This result was generally true—in our analyses, the LANDFIRE FLM fuel loading maps consistently provided lower fuel loading values in all test cases than the FCCS-based map products. This result was also found when fuel loadings were aggregated, as for the 2008 National Emissions Inventory large fires (see Figure 8 and Section 4.1.1)

The observed differences using the LANDFIRE fuel loading models approach versus the FCCS approach illustrates different philosophies in modeling fuels across landscapes.

The LANDFIRE FLM approach is to simplify the problem of how to quantify fuels across the landscape in a fashion similar to the way fire behavior fuel models were developed. Fire behavior fuel models (Anderson 1982; Scott and Burgan 2005) were created to allow calculation of the expected spread of fire through certain fuel types using the Rothermel rate of spread model (Rothermel 1972). Fire behavior fuel models were not intended to represent on-the-ground fuel loadings; rather, the fuel loadings were adjusted specifically to ensure that the fire spread calculations would work correctly. Analogously, the LANDFIRE FLMs were created to calculate expected soil heating and smoke emissions values given a set of fuel loadings (Lutes et al. 2009). LANDFIRE FLMs were not expected to represent on-the-ground fuel loadings directly. LANDFIRE FLMs were meant to provide a generalized view of fuel loadings across landscapes, rather than capture all the natural variability.

The intent of the FCCS was to quantify fuel loadings across an extensive range of vegetation types (Berg 2007). In this view, fuel models or fuelbeds that accurately represented fuels on the ground would better represent conditions on the landscape than the general fuel model approach used for fire behavior fuel modeling (Berg 2007). Rather than use a few fuel models that captured the general condition, the FCCS system is designed to create many fuelbeds to capture the extreme variability in fuel loadings observed in natural landscapes. Moreover, the FCCS system is designed to embrace the variation in fuel across landscapes; when there is no existing fuelbed for a specific fuel type, a representative fuelbed can be created. There is no limit to the number of fuelbeds that can be created using the FCCS system. Additionally, change agents can be applied to FCCS fuelbeds.

For the Tripod fire, the fuel loading maps were compared with field-sampled fuel loadings from the Current Vegetation Survey (CVS). All of the fuel loading maps were found to have low fuel loads compared to the CVS data (Drury et al. 2012). Of all fuel loading models, the best match between modeled and observed fuel loading values was provided by the OkWen Custom Fuel Loading map. Figure 13 shows the mean woody comparison for various size classes as an example. CVS plots were sampled by National Forests field crews from 1993 to 1998, corresponding roughly with the time period of the imagery used to create the OkWen Custom Fuelbeds (1998) and collect the LANDFIRE imagery (1999 to 2002) used to create FCCS2 and LANDFIRE FLMs. LANDFIRE FLM fuel loadings were consistently lower than all other fuel loading maps and were much lower than the CVS plot data.

Other work has also identified a relative bias in LANDFIRE FLMs. Importantly, Urbanski et al. (2012) showed a low bias in LANDFIRE 30-m data compared with Forest Inventory and Analysis plots in the northern Rocky Mountain region. FCCS-LF 30-m data were also examined and found to have a net low bias, but this bias was not as low or as consistent as the LANDFIRE bias.

One potential source of this bias may be the limited number of plots in the Landfire Reference Database used to create the LANDFIRE FLM map (Source: personal communication with Jason Herynk, LANDFIRE FLM map creator). With a limited number of plots, the same FLM would be assigned repeatedly across the landscape. In addition, of the plots available to assign FLMs, most had low fuel loadings. Repeatedly assigning FLMs with low fuel loadings across the landscape could lead to abnormally low fuel loadings for the entire area.

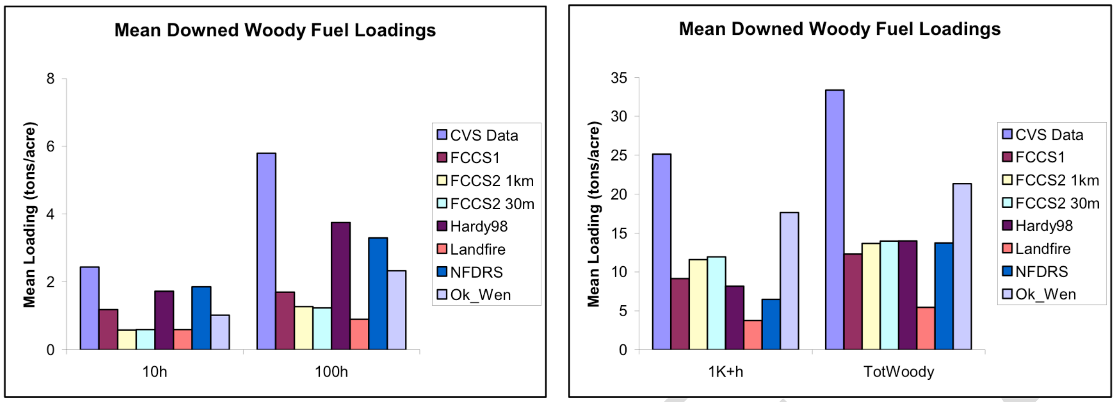


Figure 13. Mean downed woody fuel loading by model and by size, compared to sampled data for the Tripod Complex case. Adapted from Drury et al. 2012.

Conclusions

Fuel loadings are one of the largest potential sources of uncertainty in fire emissions and smoke impact modeling. Large quantified differences in fuel loadings exist among the fuel loading maps used to estimate smoke emissions. Large systemic differences exist that result in large differences even in national annual aggregates, where these differences should have been diluted. The choice of fuel loading map used to estimate fuels across landscapes will greatly influence the outcome of a smoke emissions modeling project. It is unclear whether the variations in modern fuel loading maps encompass the actual on-the-ground fuel loading. In some examples, even modern fuel loading maps have been shown to tend toward a low bias compared with plot data.

4.2.3 Total Consumption

Total consumption is one of the key parameters in understanding both fire emissions and smoke dispersion. Total consumption is the result of the translation of fuels information to consumed fuels by the consumption model. Uncertainty in available fuel information (discussed in Section 4.2.2) affects fire emissions and smoke modeling at the fuel consumption step because the amount of fuel present is a key determinant of the total fuel consumed or fuel consumed by fire phase.

There are several consumption models available. The models are based on either empirically derived algorithms or combustion physics to calculate consumption of fuels in the form of total consumption. These models may divide total consumption further by the fire phase (flaming and smoldering). In addition, total consumption can often be examined for each of the fuel layers considered by the model such as canopy, shrub, litter, or duff. Every consumption model has parameters that can be adjusted according to the modeling needs. These within-model parameters can result in different total consumption values. This additional complexity was mitigated within SEMIP by keeping within-model parameter settings constant.

One parameter setting that was investigated was fuel moisture. Most models rely on fuel moisture content in the equations calculating total consumption. Fuel moisture was adjusted to various levels to quantify the sensitivity of the CONSUMPTION output level to this parameter.

In SEMIP, we compared six different consumption models for different reasons within various case studies; the models were EPM, FEPS, Consume, FOFEM, FINN, and FLAMBE.

Key Results

These consumption models span a long history of fire research, from EPM (developed in the 1980s) and its successor FEPS (Anderson et al. 2004) through modern satellite-based emissions models (FINN, FLAMBE). EPM emissions were originally calculated using Consume 1.0 algorithms, although more modern versions of Consume (e.g., v3 and later) have differed substantially from both EPM and FEPS (Figure 14). EPM, FEPS, and CONSUME are all substantially empirically derived, while FOFEM is a dynamic (combustion physics) model. FOFEM and CONSUME were tested and adjusted with the collected pre- and post- plot data of Ottmar et al. (2011).

Modern ground-based models include Consume v3.0 (and later PYTHON based variants v4.0 and above) and FOFEM v5.7. Figure 15 shows how fuels from modern high-resolution fuel loading maps (from FCCS-LF 30m data and the LANDFIRE 30-m data, see Appendix C.2) process through these modern consumption models for the Bugaboo Complex test case (see Appendix B.5). Consume and FOFEM model fuel consumption through a range of fuel layers or strata including canopy, shrubs, herbaceous, downed and dead woody fuels, stumps, snags, litter, and duff. Consume algorithms are more empirically based while FOFEM uses a combination of algorithms based on empirical studies and combustion physics. Total consumption produced by Consume versus FOFEM varies by vegetation type. Test cases such as the 2006 Tripod Complex illustrate these variations. In the 2006 Tripod Complex fire area, Consume produced higher consumption rates for deep duff layers in more densely forested areas while FOFEM produced higher duff consumption rates in more open vegetation types.

The FINN model is simpler than Consume or FOFEM in computing fuel consumptions. Fuel loadings in two classes (woody fuels and herbaceous cover) are assigned a fraction burned as a function of tree cover (Wiedenmyer et al., 2010). In the sensitivity analysis described in Section 4.1.1, this method yielded about 50% of the consumption estimated from Consume and FOFEM (see Figure 8). This difference may be due in part to the lack of ground fuels in the FINN method.

Of all the consumption approaches assessed in SEMIP, the FLAMBE method is the simplest. A fraction consumed is assigned based on land cover type. For forest lands this value is 0.5, and for grasslands the value is 0.85. Given the difference in approach and complexity, FLAMBE consumption results for the large fire sensitivity analysis (Section 4.1.1) were remarkably similar to the consumption results from the FCCS-Consume and FCCS-FOFEM pathways (see

Figure 8). The FLAMBE methodology is necessarily simple to support global-scale operational smoke forecasting.

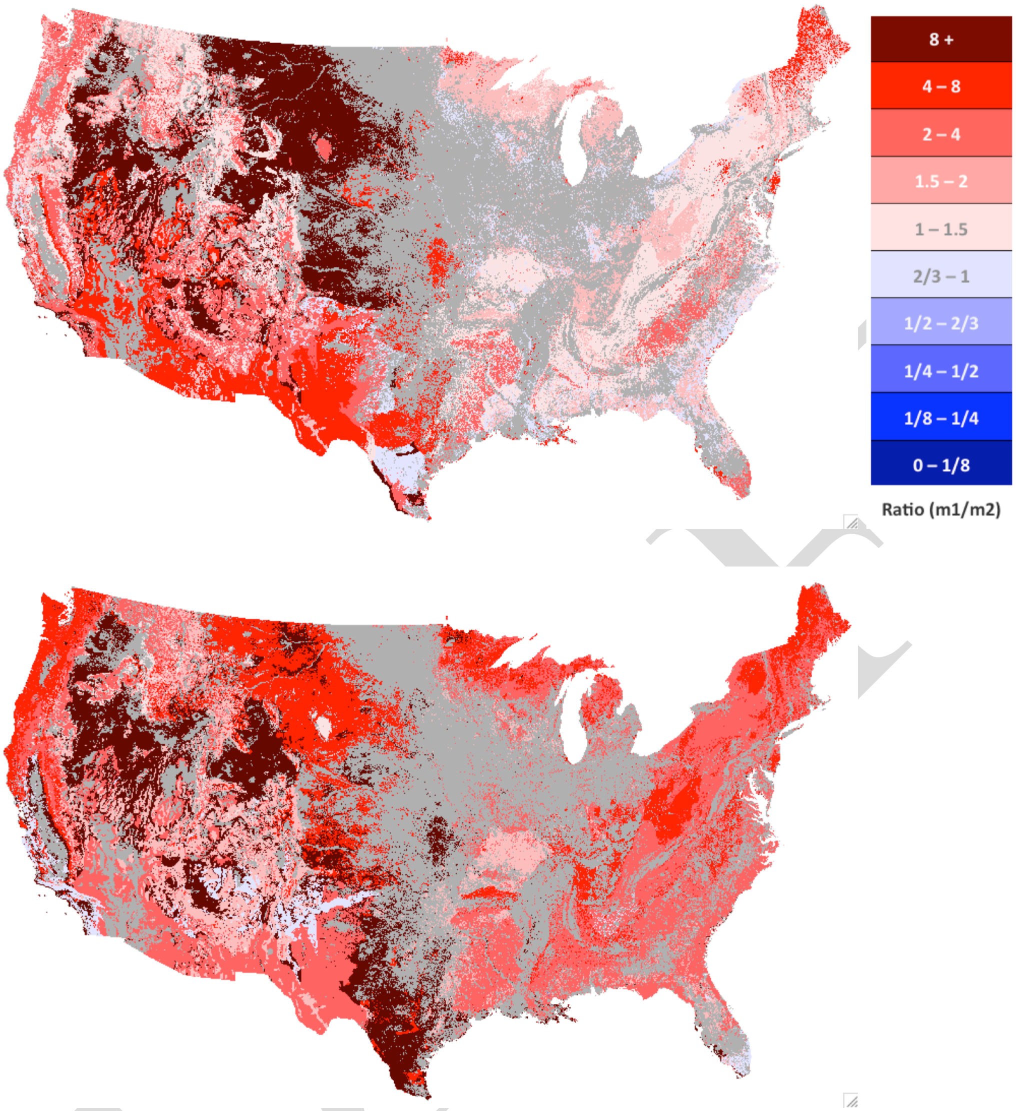


Figure 14. Relative consumption between different models. Top: Ratio of Consume 3.0 to FEPS v1.1 consumption using FCCS v1 fuels. Bottom: Ratio of Consume 3.0 to EPM using FCCS v1 fuels. From the Fires Everywhere case (see Appendix B.1 for details). In both cases, Consume is seen to compute significantly more total consumption than FEPS or EPM, but the relative ratios vary considerably and show significant point-to-point variation.

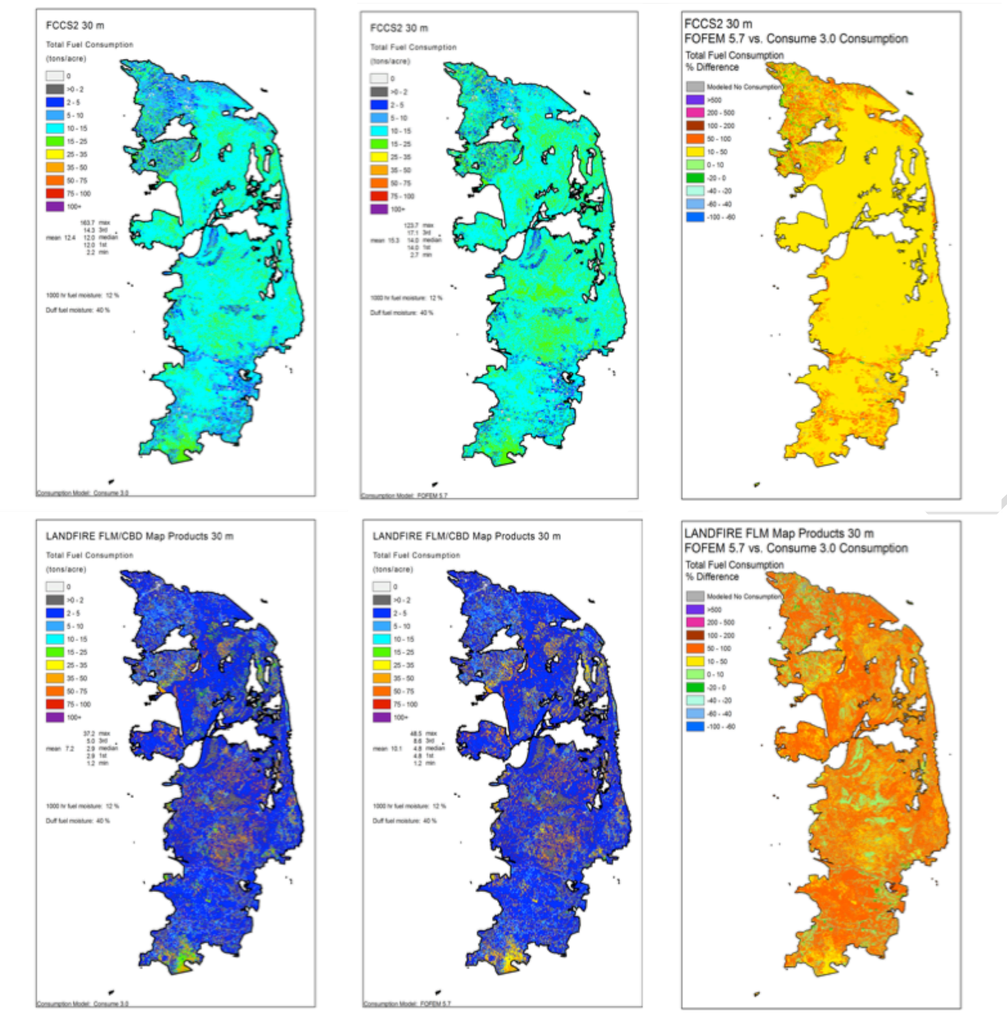


Figure 15. Fuel consumption differences using FOFEM vs. Consume for the Bugaboo Fire Complex. The upper panels contain Consume and FOFEM output using the FCCS-LF (labeled here as FCCS2) as the fuel loading input, and the lower panels present Consume and FOFEM output using the LANDFIRE FLM maps. Adapted from Drury et al. 2012.

Fuel Moisture Sensitivity

Fuel moistures are required inputs to Consume and FOFEM. The capacity for fuel to sustain ignition and be consumed is based on fuel moisture content. Consumption in wet fuels is typically lower than in drier fuels (Figure 16). While both models show a decrease in consumption with increasing fuel moisture, the threshold for burning for each fuel layer varies between Consume and FOFEM.

Furthermore, non-fuel moisture inputs to Consume and FOFEM were manually applied to the sensitivity analysis shown in Figure 16 to present reasonable assumptions of how canopy fuels and shrub fuels would consume under varying fuel moisture conditions. Percent canopy consumed for Consume and FOFEM was subjectively set to 95% for the very dry case and progressively decreased in 5% increments to 0% for the very wet case (Figure 16, from the 2006 Tripod Complex test case). Shrub consumption in Consume was subjectively determined by manually setting the parameter, percent area blackened, to 95% for the very dry case and progressively decreasing it to 0% for the very wet case. FOFEM internally defaults shrub consumption to values ranging from 50% to 90% depending on season of burning and vegetation type. Subjectively setting canopy consumption and shrub consumption resulted in a gradual decrease in fuel consumed for these layers as fuel moisture increased.

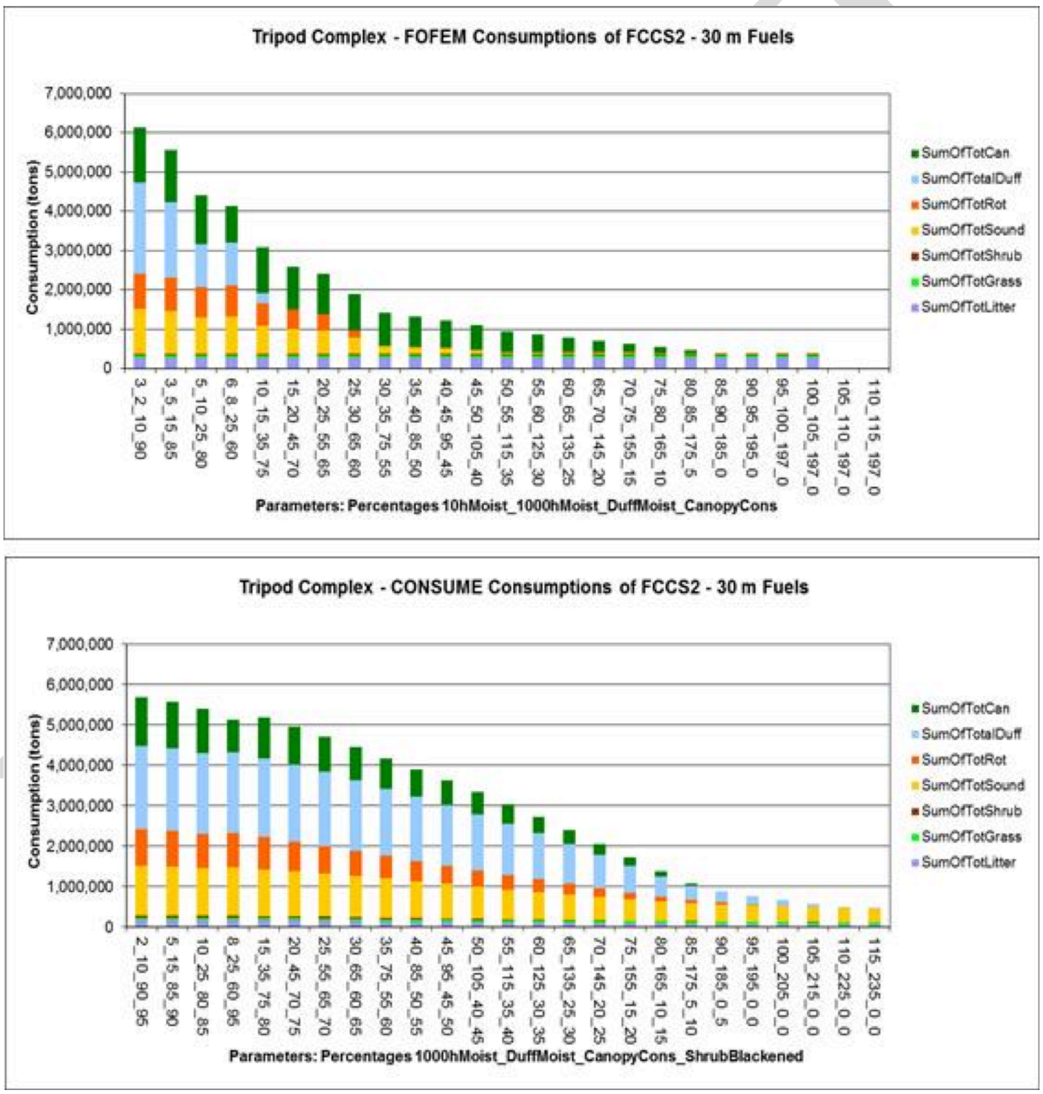


Figure 16. Pattern of fuel consumed with increasing moistures in FOFEM (top) and Consume (bottom).

Consume and FOFEM produced similar estimates of all sound and rotten woody fuel (1-, 10-, 100-, 1000-hr combined) consumption at low moisture levels, but as moisture levels increased the model outputs diverged (Figure 16). In FOFEM, woody fuel consumption stopped when fuel moisture reached 30% for sound wood and 55% for rotten wood. Consume continued to estimate woody fuel consumption at much higher moistures. In Consume, rotten woody fuels continued to consume until fuel moistures reached 185% for sound wood and 235% for rotten wood.

Duff moisture relationships to duff consumption followed similar trends. Duff consumption reached a moisture threshold and stopped burning in the FOFEM simulations at duff fuel moistures of 45%. In the Consume simulations, duff continued to burn until fuel moistures were set to 205%. In contrast, litter consumption using FOFEM remained fairly constant across the range of fuel moistures tested, while Consume estimated progressively lower rates of litter consumption as fuel moisture increased.

The differences in consumption at high fuel moisture values and in duff consumption are important to note because they will directly affect the emissions in the next modeling step. It is important to use appropriate fuel moisture values when modeling smoke emissions and to understand the type of duff consumption that is relevant to the location under consideration. Throughout the course of the SEMIP project, care was taken to use representative fuel moistures for each region. Fuel moistures were applied consistently to ensure that the uncertainty noted at the CONSUMPTION output level was due to the model and not the fuel moisture applied.

Fuel moisture content and duff depth are influential parameters that will change total consumption results. In addition, fuel moisture content and duff depth are good examples showing how the CONSUMPTION modeling step is influenced by the FUELS modeling step. These results will further influence model pathway results at the emissions or smoke dispersion output levels (see Section 2.3).

Modeled fuel consumption outputs from Consume and FOFEM for the 2006 Tripod Complex were compared with a set of field observations linked to satellite-derived burn severity indices from the MTBS project. Justice et al. (2009) conducted a study that linked field estimates of fuel consumption (canopy, shrubs, woody fuels, and duff) to the MTBS burn severity indices (no burn, high, medium, low severity). We compared the MTBS/Field observations with the mapped fuel consumption model estimates pixel by pixel (Figure 17). Consume consistently estimated the highest fuel consumption, and FOFEM estimated the lowest fuel consumption. The MTBS observed fuel consumption values fell within the two model estimates.

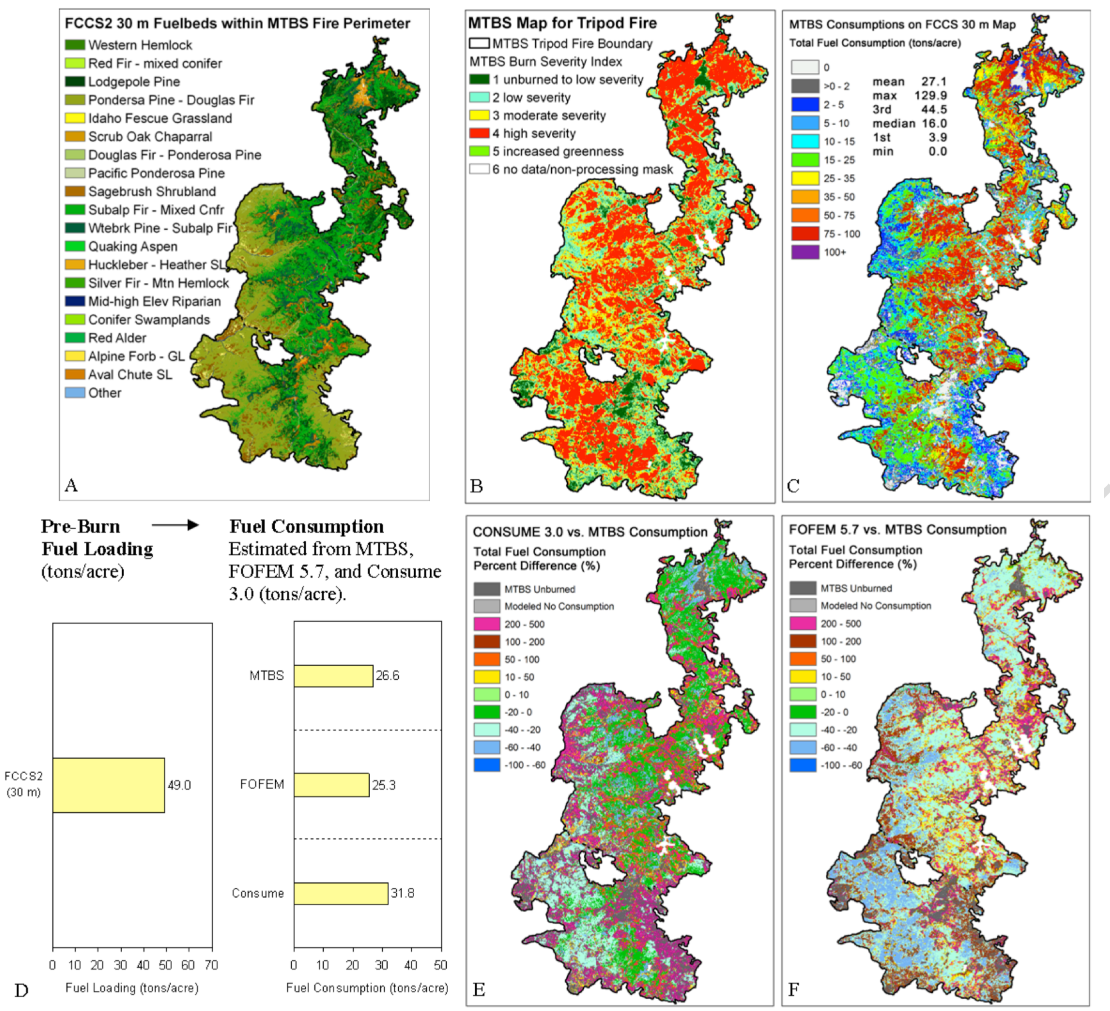


Figure 17. Fuel consumption intercomparisons among FOFEM, Consume, and the MTBS field based fuel consumption estimates for the 2006 Tripod Complex. Total consumption was consistently higher for Consume vs. FOFEM. The observation based MTBS fuel consumption estimates fell between the two model outputs (From Drury et al. 2012).

Conclusions

Although FOFEM and Consume differ in their handling of fuel layers, they provide reasonable fuel consumption estimates when the fuel information represents physical reality. FOFEM and Consume produced fuel consumption estimates in agreement with the best landscape level fuel consumption observations available at this time. Older consumption models (e.g., EPM, FEPS) differ substantially from each other and from FOFEM and Consume. Global scale models such as FINN and FLAMBE sometimes produce considerably different results from Consume and FOFEM. This is somewhat expected given that they calculate consumption using land-cover-based lookup tables that are independent of fuel moisture. Improvements in landscape level fuel loadings would improve the accuracy of fuel consumption estimates. At this time, there is more uncertainty surrounding our ability to estimate fuel loadings than fuel consumption.

4.2.4 Time Profile of Consumption

The time profile of consumption allocates the total fire emissions and heat hourly throughout the course of the day. This is an important step in the smoke modeling pathway, as hourly emissions are needed to determine both plume rise and dispersion. Assigning emissions and heat to specific hours throughout the day is critical to correctly model interactions with the planetary boundary layer including plume injection height calculations, and for correctly placing emissions within the ambient synoptic wind field. Thus, incorrect time profiles can lead to errors in surface smoke concentrations. In addition, the diurnal placement of emissions directly affects the chemical processes modeled by chemical transport models (i.e., CMAQ).

A common diurnal consumption profile for temporally distributing wildfire emissions is the profile specified by the Western Regional Air Partnership (WRAP, 2002). The WRAP based their diurnal consumption profile on the consensus of expert knowledge of wildfire behavior in the western U.S., where fire behavior begins to increase in the morning, reaches a peak in the mid-afternoon (1600 hours local time), and subsides in the evening. Over 90% of the emissions occur over a 10-hour period. The WRAP diurnal profile accounts for both the flaming and smoldering phases of the fire within one profile curve. See Appendix B for additional information. For prescribed fires, emissions are often distributed according to the exponential decay algorithm found in the FEPS model. This model further separates emissions by fire phase; flaming, smoldering, and long-term smoldering.

To test both time profile curves, the Naches, Washington, prescribed fire was modeled separately as a wildfire and as a prescribed fire. Changes were made to the WRAP and FEPS time profile curves (see Appendix B for more information) and the output analyzed to assess smoke dispersion sensitivity to changes in the time profile of consumption. For each curve, changes were made both to the starting time (by time shifting the curve forward or backward throughout the day) and to the shape of the curve (by making it more "peaked" with a higher maximum and narrower time range, and by making it more "flat" with a lower maximum and emissions spread more throughout the day). Metrics of the modeled smoke consumption (e.g., maximum modeled concentration, average modeled concentration, and area modeled as having a concentration greater than a number of different thresholds) were calculated to investigate the spatial and temporal effects these time profile variations had on the resulting 1-hr $PM_{2.5}$ concentration fields (see Appendix D for additional information).

Key Results

Time profile changes resulted in very large changes to maximum concentration and large changes to other metrics. In particular, time shifts that moved the emissions into non-daytime hours appeared to interact with the planetary boundary layer heights to produce strong shifts in the modeled smoke concentrations. For example, Figure 18 shows the results of shifting the WRAP time profile on maximum concentration, average concentration, and total area with over 35 ug/m^3 hourly concentrations at any time in the simulation. Shifting the WRAP profile by as little as 2 hours resulted in significantly higher maximum $PM_{2.5}$.

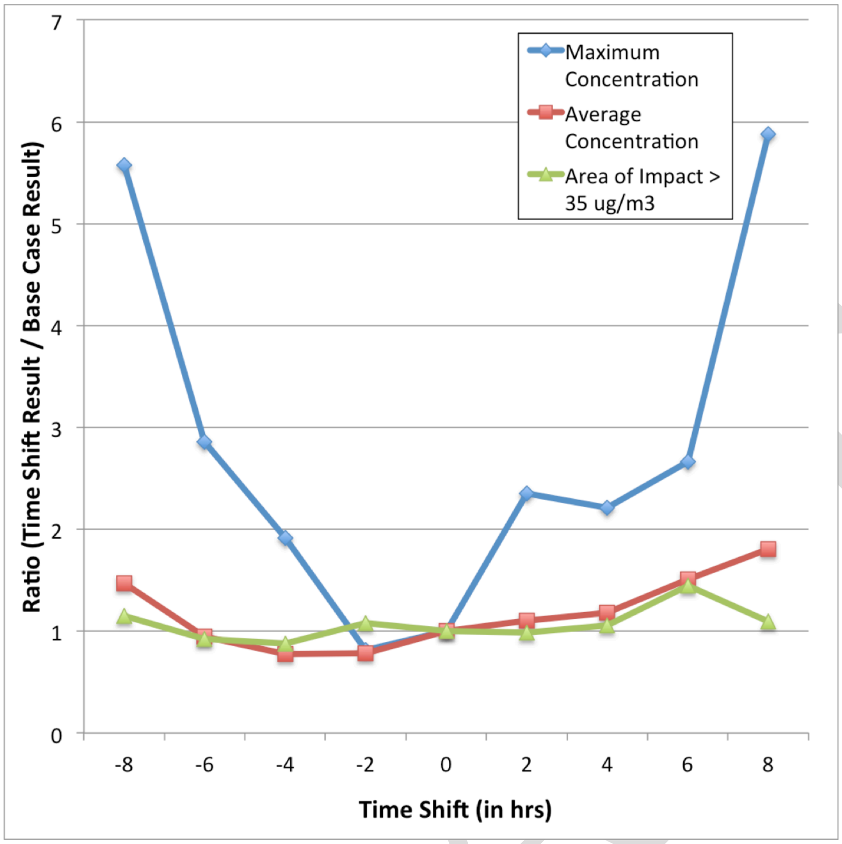


Figure 18. Changes in domain maximum concentration, domain average concentration, and total area of impact > 35ug/m^3 based on time shifting the WRAP profile in the Naches prescribed fire test case. A value of one indicates no overall change to the metric; a value of two indicates that the time shift resulted in a doubling of the overall metric.

Time shifts and time profile changes can also create large changes in the overall area of impact. While Figure 18 shows little overall change in the amount of area affected by simply shifting the time profile curve, Figure 19 shows that such shifts can alter the specific locations affected.

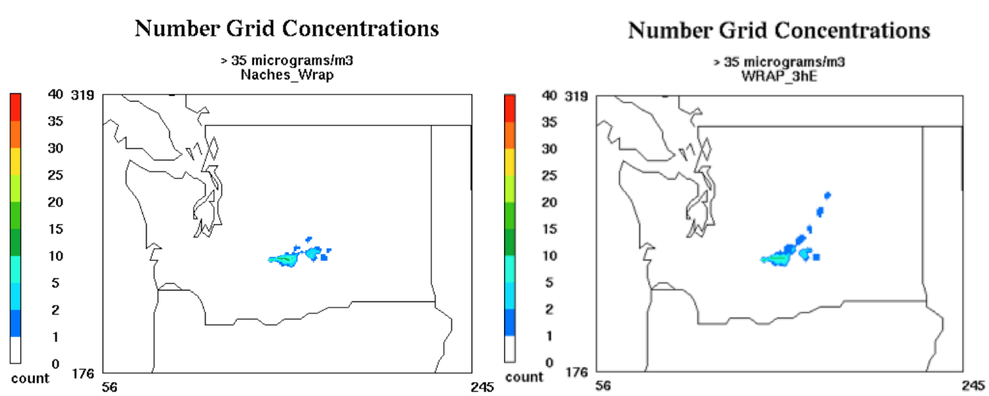


Figure 19. Locations affected by >35ug/m^3 smoke concentrations for the normal (left) and 3 hour earlier (right) WRAP time profile.

Conclusions

The time profile of consumption and/or emissions is among the least studied and least verifiable components of the modeling chain, yet sensitivity studies show that modeled smoke concentrations are highly sensitive to errors in this modeling step. Significant work is needed to identify and gather observations and models capable of reducing this uncertainty and incorporate them into current smoke modeling systems.

4.2.5 Emissions

Common pollutant emissions estimated from wildfires or prescribed burns include CO, CO_2, CH_4, PM, $PM_{2.5}$, PM_{10}, NO_x, NH_3, and SO_x. Emissions estimates are made using emission factors either derived from empirical algorithms, such as those used by the Fire Emissions Production Simulator (FEPS) model (Anderson et al., 2004), or derived from laboratory or field observations (e.g., Yokelson et al., 2008; Ward and Hardy, 1991). Speciated emissions are a function of fuel type, fuel moisture, and fire behavior phase (flaming vs. smoldering). Emission factors, either modeled or derived from observations, describe the mass of species emitted per mass of fuel consumed and are used to determine the levels of each species in the smoke plume.

There is evidence that nitrogen content in the soil influences the emission of nitrogen-based species such as NO_x ($NO_x = NO + NO_2$) and NH_3 (McMeeking et al., 2009). New emission factor algorithms would have to be added to the models to account for this relationship. Unfortunately, the relationship of soil nitrogen content and emissions appears to be highly dependent on soil type and regional location. The sensitivity of emissions of nitrogen oxides to these local variables remains largely unknown at this time.

Six emission models were tested and a comprehensive literature review was undertaken to gain an understanding of emission factors derived from observations. The models included: EPM, FEPS, Consume, FOFEM, FINN, and FLAMBE (see Appendix C.5 for definitions and references).

Key Results

Emissions were tested and compared within various test cases. For a majority of the fuel and consumption model combinations tested in the 2008 National Emissions Inventory, emissions from the Consume and FOFEM models were higher compared to the FINN emissions (see Figure 8). Emissions from the models with the LANDFIRE fuels information were less than or equal to the FINN emissions. The FLAMBE model produced nearly double the emissions compared to the other emission pathway combinations. This is somewhat expected given the coarse fuel information scheme and relatively simple consumption algorithms used within the FLAMBE system.

The 2006 Tripod Complex was used to examine emissions from a single wildfire event. Consume and FOFEM model results were compared. Because of the way the emissions factors and associated algorithms are applied within FOFEM and Consume, we investigated consumption-emission pairings in the form of FOFEM consumption with FOFEM emissions and Consume consumption with Consume emissions. The FOFEM-FOFEM combination produced higher emissions for CH_4, CO, $PM_{2.5}$, and PM_{10}, while the Consume-Consume combination estimated higher emissions for CO_2. The Consume combustion model consistently estimated a higher consumption of fuels compared to the FOFEM combustion model.

In general, the emission factors within FOFEM are higher than those used within Consume. In addition, the ratios of fuel going into the smoldering or flaming phase of emissions vary between the models (see Appendix D.3). Emissions by fuel type were examined and FOFEM produced higher emissions for the dense conifer stands while Consume produced higher emissions for the open pine stands. The higher total emissions for the 2006 Tripod complex from Consume versus FOFEM are a direct result of the conifer fuel type covering more area than the open pine stands,

A literature search was done to collect emission factors reported for vegetation species within the United States between 1984 and 2010. There are several reviews of literature factors within the peer-reviewed arena (e.g., Akagi et al., 2010), however these reviews discuss emission factors based on global fuel types such as ‘savanna’ or ‘boreal’. Collections of new global emissions factors are also available (e.g. Burling et al. 2011). This review focused on vegetation species more specific to the United States.

In several manuscripts, combustion efficiency was reported alongside the emission factors. Combustion efficiency reflects the phase the fire is in: flaming or smoldering. The association of emission factors to combustion efficiency allows for further understanding of the primary phase of the fire under which the emission factors were derived. The FEPS model uses linear relationships between the emitted species and combustion efficiency. These algorithms do not change by vegetation type, as it is assumed that the FEPS-calculated combustion efficiency reflects combustion phase, and hence emissions, appropriately.

Combustion efficiencies found in the literature were used with the FEPS algorithms to compute emission factors for CO_2, CO, CH_4, and $PM_{2.5}$. This was done to evaluate the FEPS-computed emission factors against those derived from observations.

Emission factors computed using the FEPS equations with observed combustion efficiency values ranged in difference compared to the emission factors derived in the field. The difference varied by chemical species and by vegetation type. For CO_2 and CO, the FEPS results matched the field results for the Ponderosa pine and Douglas fir vegetation types, but for the chaparral and sagebrush vegetation the FEPS results were shifted off of the observations (Figure 20). Black spruce is interesting, for CO_2 the model results are very near the observations while for CO the modeled results show a similar trend but are shifted towards lower values. For CH_4 and $PM_{2.5}$ the FEPS results are shifted from those collected in the field for all vegetation types (Figure 21).

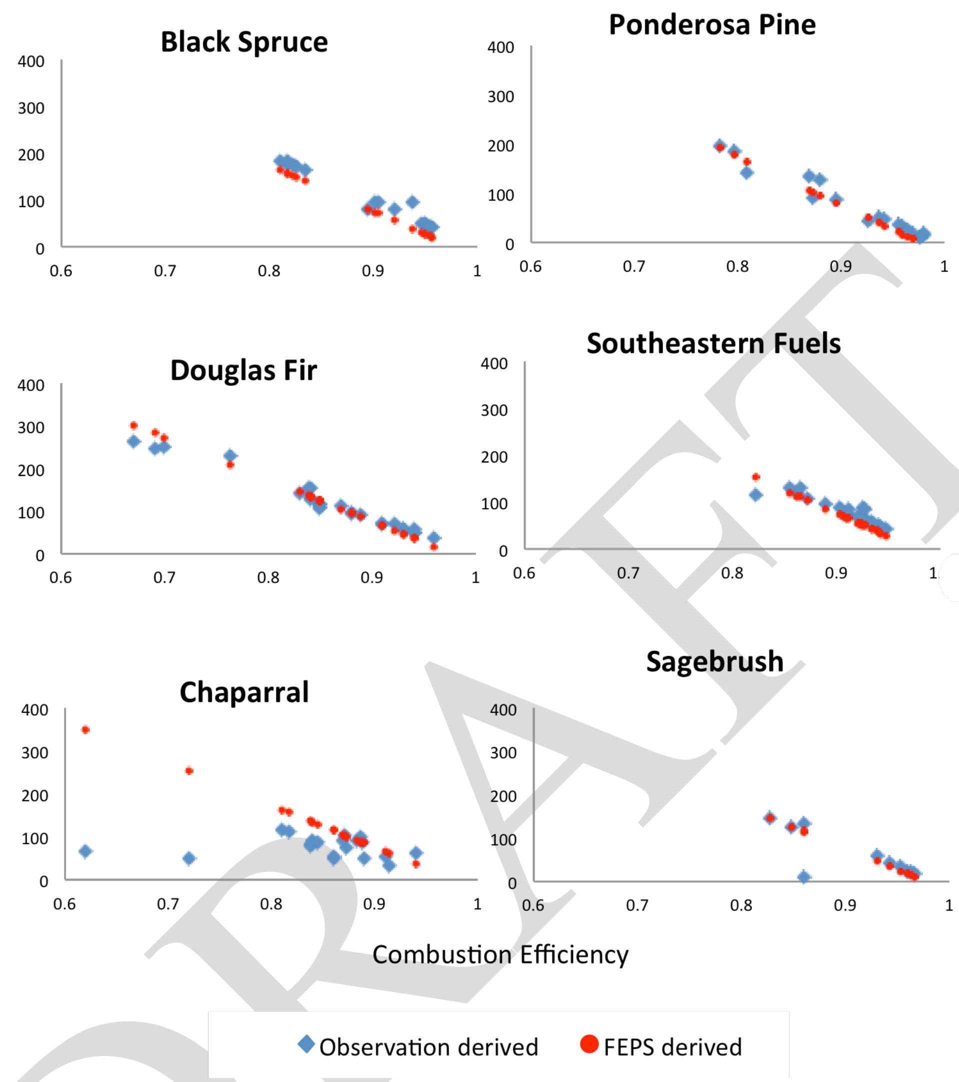


Figure 20. CO emission factors in grams emitted per kg of fuel consumed (y-axis) verses observed combustion efficiency (x-axis). Blue circles represent CO emissions produced using emission factors derived from observations and red circles represent FEPS calculated CO emissions using FEPS emissions factors.

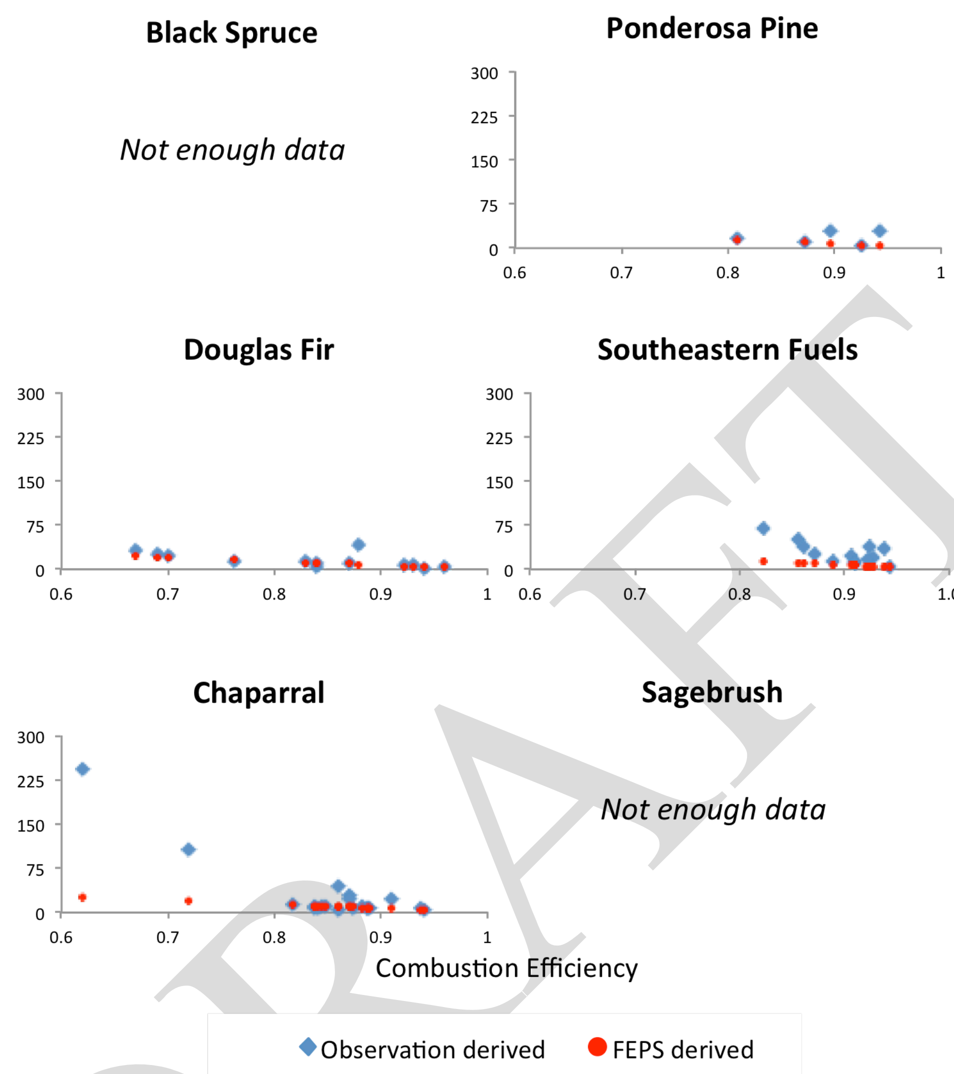


Figure 21. $PM_{2.5}$ emission factors in grams emitted per kg of fuel consumed (y-axis) verses observed combustion efficiency (x-axis). Blue circles represent $PM_{2.5}$ emissions produced using emission factors derived from observations and red circles represent FEPS calculated $PM_{2.5}$ emissions using FEPS emissions factors.

There are incidences where the modeled results are greater or less than the observations but the slope of the modeled results is close to the slope of the observation-derived emission factors (e.g., sagebrush CO_2, Black spruce CO, and chaparral CH_4). This indicates that the empirically derived equation produces the correct trend relative to combustion efficiency but not the correct quantity of emitted mass per mass of vegetation consumed. In other cases, the slope of the modeled results is more extreme or less than those derived in the field. For these instances, the empirical algorithm has failed to reproduce the relationship between emitted species, combustion efficiency, and vegetation type.

Conclusions

Within the Tripod Complex, FOFEM produced higher emissions for all species except for CO_2 when compared to Consume. This was due to the handling of the different fuel types found within the fire complex (dense conifer vs. open pine). The handling of smoldering versus flaming phases by the models played a large role in these emission differences.

In general, the variation found in the previous output levels (FUELS, CONSUMPTION) remains in the output after the emissions modeling (Figure 8). This could be due to the use of the simple linear or constant empirical relationships to calculate emission factors within each model.

A majority of the observation-derived emission factors and corresponding combustion efficiencies were centered on six regional fuel types (Ponderosa pine, Douglas fir, chaparral, sagebrush, Black spruce, and southeastern fuels). Expanding observation-derived datasets for the unstudied fuels (i.e., Mountain pine) will assist with model evaluation in the future.

The empirically derived emission factor equations used within the emission calculators may not fully represent the observations made over the last three decades. Sensitivity to the empirical relationship is high for $PM_{2.5}$ emission factors; however, it is relatively low for CO_2 and CO.

4.2.6 Plume Rise

Plume rise is the lofting of freshly emitted smoke that occurs due to buoyancy and entrainment. The amount of plume rise over a given fire depends on a number of factors, including heat flux and prevailing meteorology. Plume rise models apply these factors to estimate the plume injection height, which is the vertical zone in which the plume begins horizontal transport away from its source. Correct prediction of plume rise is important for both near-field estimations of ground-level pollution and long-range transport. Unfortunately, plume rise observations are not common and most plume rise models have undergone little, if any, validation in wildland fire conditions.

The emergence of two satellite-derived datasets that provide information on plume heights over a large number of fires presented an opportunity for the validation of plume rise estimates from a modeling pathway. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and the Multi-angle Imaging Spectroradiometer (MISR) instruments both provide unprecedented vertically resolved information on smoke (Kahn et al. 2007; Winker et al. 2009). The use of CALIPSO data required substantial plume discovery and preprocessing effort, while the MISR-derived plume heights were acquired from the MISR Plume Height Project (NASA 2011). Previous work has shown the value of the MISR Plume Height Project data in assessing fire heights over North America (Val Martin et al., 2010). 64 CALIPSO plumes and 163 MISR plumes between 2006 and 2008 over the contiguous U.S. were matched to modeled plume heights. Because the two instruments are onboard satellites with different orbits, the datasets are independent. A full presentation of methods and results is available in Raffuse et al. (2012).

Key Results

Figure 22 shows individual model-to-MISR comparisons for individual plumes. In general, MISR plume heights are low in the east and higher in the west. Modeled plume heights compared poorly, with an overall correlation coefficient r = 0.32. Figure 23 shows the plume height results categorized by fire size. This shows that the model pathway underpredicted plume rise for small fires, while overpredicting for large fires.

Because plume rise estimates are dependent on all steps upstream in the smoke modeling chain, it is difficult to assess plume rise algorithms independently. Key factors that influence plume rise include the active fire size, available fuel, fuel moisture, consumption rate and timing, and atmospheric conditions. Many of these factors are uncertain.

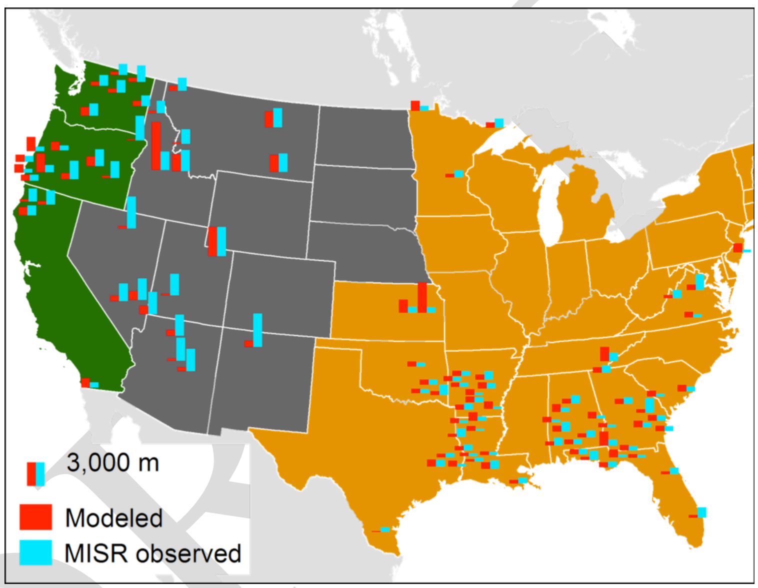


Figure 22. Map of modeled and MISR-observed plume heights (reproduced from Raffuse et al., 2012).

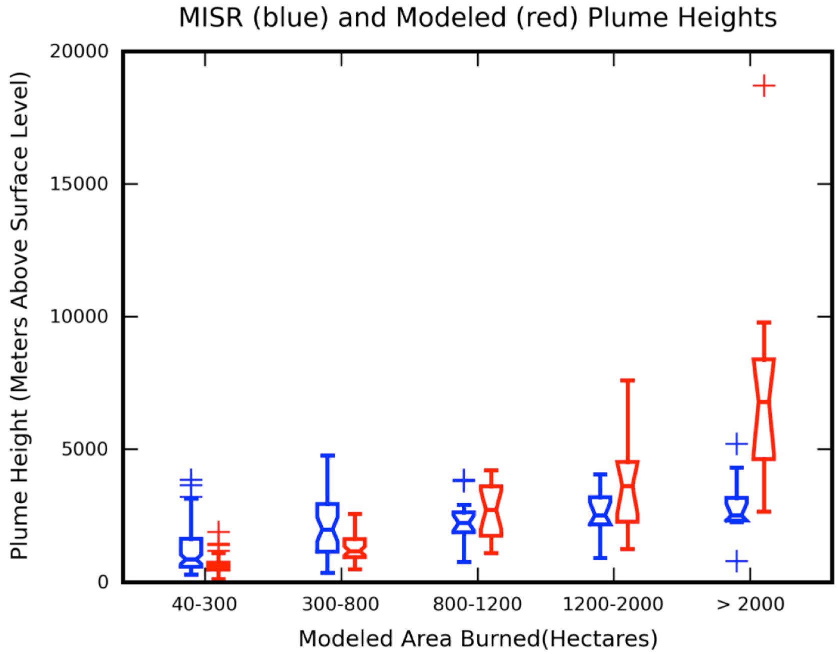


Figure 23. Box plot of modeled (red) and MISR-observed (blue) plume heights as a function of modeled area burned.

Conclusions

Researchers and model developers who wish to build upon plume rise results from SEMIP should consider the following recommendations. Sensitivity studies should be conducted to understand the critical factors driving differences in both modeled and observed plume heights. Additional model pathways, including those with new, fire-specific plume rise models, should be validated with remotely sensed data products. While the CALIPSO data offer valuable high-resolution observations of aerosol vertical profiles, they are laborious to acquire, process, and match with modeled smoke plumes. In contrast, the MISR Plume Height Project is an excellent resource for validating plume rise models. As of now, the project has analyzed eight years of plumes over North America.

4.2.7 Dispersion

Predicting smoke transport/dispersion and ground concentrations of fine particulate matter ($PM_{2.5}$) or other gases (i.e., CO, NO_x) is the final step in the Smoke Emissions Modeling Intercomparison Study. This step relies on all previous modeling steps: fire information, fuel type and moisture, fuel consumption, time rate of consumption, speciated emissions, and plume rise. The Naches test case was used to evaluate the sensitivities of computed ground smoke concentration parameters with respect to various modeling steps in the overall smoke impact modeling chain (see Section 4.1.2 for more information). The northern California wildfires test case was used to compare modeled surface $PM_{2.5}$ concentrations to observations.

The California wildfire test case consists of two wildfire events: the adiabatic-wind-driven event in southern California in October 2007; and the lightning-ignited event in northern California in July 2008. These analyses evaluated the predictions of hourly $PM_{2.5}$ surface concentrations produced by the BlueSky Gateway modeling system and posted to the BlueSky webpage on a daily basis. The modeling system used SMARTFIRE v1 (Raffuse et al., 2009) for fire information; the Fuel Characterization and Classification System (FCCS; McKenzie et al., 2007), Consume v3 for total consumption modeling (Ottmar et al., 2002); the Fire Emissions Production Simulator v1 (FEPS; Anderson et al., 2004) for Rate of Consumption and Emissions; and the Western Regional Air Partnership (WRAP) method for plume rise. The surface concentrations were produced by the Models-3/Community Multiscale Air Quality model (CMAQ; Byun and Ching, 1999) after going through the SMOKE v2.3 modeling system, where emissions from other sources were merged with the wildfire emissions.

Key Results

The results of these analyses demonstrate BlueSky Gateway prediction bias and reveal system strengths and weaknesses that point to areas in need of further research and model development. A brief summary of results is provided below. A detailed description of the analyses and results can be found in Strand et al. (2012).

For the California dispersion level case study, overall performance was marginal for the Southern California fires and good during the Northern California fires. Model performance varied considerably within the wildfire events, depending on the prevailing synoptic flow patterns for the southern California portion of the study and the observation site relative to local terrain for the northern California portion of the study.

Any error in fire location or total fuel type consumption will propagate into the predicted values, and for this case study the accuracy of simulated $PM_{2.5}$ concentrations was limited by available real-time data used to characterize the fires. In addition, the model grid spacing, chosen for producing national predictions by 7 AM eastern US time, may have been too coarse to resolve terrain-induced winds and resulting smoke plume transport that occurred during this test case.

During the 2007 Southern California fires, the model performance was differentiated by synoptic flow: performance was considerably better for onshore flow periods compared to the offshore flow periods (Figure 24, left). This was likely due to the differences in mixing processes prevalent in the lower boundary layer. During offshore periods the atmosphere was less horizontally mixed, making observed values at monitoring locations more locally controlled. During the 2008 Northern California fires, the model performance was differentiated by valley type: narrow-valley predictions performed less well than broad-valley predictions (Figure 24, right). This is expected given the coarse scale of the model and its inability to properly resolve the narrower valleys.

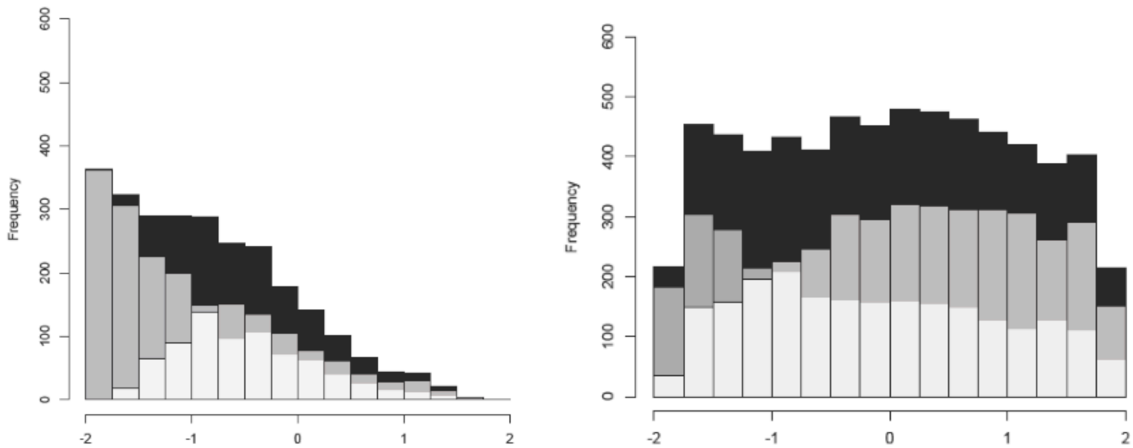


Figure 24. Distribution of the fractional bias of hourly predicted values for the Southern California (left) and Northern California (right) wildfire events. A perfect prediction would result in a fractional bias of 0. The data were placed into fractional bias bins (every 0.25, x-axis). The number of values within each bin was counted and plotted (frequency, y-axis). For Southern California (left), all of the data (black bars), offshore portion (grey bars) and onshore portion (white bars) are shown. For Northern California (right), all of the data (black bars), broad valley (grey bars), and narrow valley (white bars) are shown. Figure from Strand et al. (2012).

Conclusions

These results show that even within one wildfire event, several processes are at play that influence overall model performance. Future analyses with predicted $PM_{2.5}$ concentrations with output from a model driven with meteorology from a finer grid resolution are needed to quantify the reduction in predicted $PM_{2.5}$ concentration error. The relative contribution of the error introduced into the results by the modeling grid size versus the error propagating from the modeling pathway (fire information, fuels, consumption, time rate, emissions, and plume rise) is unknown. Further analyses using the various SEMIP modeling steps may lead to further improvements in fire emissions source characterization.

5. CONCLUSIONS

5.1 Key Overall SEMIP Findings:

The need to share and maintain data

- Access to the result of projects both in terms of observational data and model code has been problematic.
- Perhaps in part because of recommendations arising out of SEMIP, data access issues are now being directly addressed by the JFSP.
- Questions remain as to whether the preferred archives (e.g., the USFS Data Archive) are capable of and interested in housing the *ancillary* (not directly observed) data required to maintain a functioning test case. Of particular concern is meteorological model output (e.g., from the National Weather Service) which can have sizes from 10s of Gigabytes to Terabytes, but which are required to enable standardized smoke modeling.

The need for test cases

- While there are a lot of scattered data available, making a worthwhile focus (test case) for extended study requires a *density* of data that is harder to find in order to allow for many different comparisons and analyses.
- In particular, addressing questions with regard to smoke modeling requires data from all parts of the fire modeling chain—fire behavior, fuels, consumption, emissions, plume structures, meteorology, and smoke impacts (i.e., plume chemistry, surface concentrations).
- Perhaps in part because of recommendations arising out of SEMIP, the JFSP has embarked on a large-scale observational campaign (RX-CADRE). Such campaigns have the potential to provide new and useful test cases for a wide range of modeling.

Biggest uncertainties

- The biggest uncertainties in modeling depend on the needed use case:
    - real-time vs. retrospective
    - aggregated vs. localized
    - diurnally resolved vs. annualized.
- For national annual fire emissions, the biggest uncertainties are:
    - Area burned
    - Fuel loadings
    - Emissions factors for trace gasses and particulates
- For smoke impacts the biggest uncertainties are:
    - Fire growth per hour (both size and diurnal timing)
    - Plume rise
    - Fuel loadings
    - Plume chemistry is also a known uncertainty; however, this was not studied within SEMIP

5.2 Summary of SEMIP Findings by Modeling Step

Table 1. SEMIP findings for each modeling step.

Modeling Step	Summary of SEMIP Findings
Fire Information	Community-accepted methods of reconciling fire information datasets to one complete, cohesive whole needed. (Note: this is the focus of current JFSP projects under the latest RFA).
Fuels	Newest datasets (LANDFIRE-FCCS 30m/1km and LANDFIRE 30m) are not in close agreement. Need significant fuel-research-led effort to determine why and how to determine the best dataset for a given area.
Consumption	Models compare reasonably well overall. However, there are significant issues with certain fuel components (e.g., deep organics, shrubs, canopy, etc.).
Time Rate	A large unknown, particularly for wildfire. Intrinsically related to fire behavior and the lack of reliable fire behavior predictions.
Emissions Factors	Need to focus research on smoldering vs. flaming EFs; $PM_{2.5}$ and NO_x along with lesser emitted species (VOCs, BC) including toxics; may need vegetation-specific emissions factor work.
Plume Rise	A major unknown. Statistical corrections to current models possible using large-scale comparisons like ones done here, but dynamic plume models with realistic plumes awaiting fire behavior modeling advancement.
Dispersion	Dispersion models appear not to be the current weakest link in the smoke impact chain. Results are critically dependent on the plume rise, time rate, and overall emissions calculated as well as the accuracy and grid scale of the available meteorological models.
Plume Chemistry	Not currently assessed within SEMIP. This would be a logical next step for SEMIP.
Fire Behavior	Note: many issues above (time rate, plume rise) point to the need to advance fire behavior modeling. These models were not assessed as part of SEMIP. However, our findings point to the need for advances in fire behavior modeling done *specifically for smoke modeling* purposes to predict: fire growth, consumption, and emissions by hour or sub-hour timestep (including how these emissions are organized into convective "cores" or plumes).

5.3 List of Key Findings

- Fire information errors are critical to smoke impacts
- Fire information is most uncertain for prescribed burning at the national scale
- There is no available national dataset of fire occurrence for fires < 1000 acres
- Many small fires are undetected by current satellite-based methods
- Fire type (wildfire, prescribed, agricultural) is of importance for emissions inventories and not available from remotely sensed fires
- Pile burning is not well recorded, characterized, or estimated in emissions inventories
- Fuels are critical to both fire emissions and smoke impacts
- Older fuel loading maps were often not built for fire emissions modeling and should not be avoided for modeling fire emissions and other fire effects
- Modern fuel loading maps still show large and systemic differences, which include large differences in:

    - Canopy fuels
    - Snags
    - Shrub Fuels
    - Stumps
    - Deep organic fuels
    - Proportion of rotten and sound fuel
- In limited tests, even modern fuel loading maps have been found to be low-biased against field plot measurements
- Modern consumption models agree better than modern fuels datasets
    - duff consumption is a major uncertainty
    - canopy consumption is a major uncertainty
    - shrub consumption is a major uncertainty
- The differences in the split between smoldering and flaming is significant even in modern consumption models (Consume, FOFEM)
- Emissions factors need updating across the board, with primary emphasis on $PM_{2.5}$ and trace gas emissions (e.g., BC, VOCs, etc.)
- Diurnal profile uncertainties are unknown
- Surface smoke concentrations can be very sensitive to how temporal emissions are treated with the time profile of consumption, especially when planetary boundary layer height is low
- Time rate data, including data from fire growth models, is extremely lacking
- Plume rise errors are critical to smoke impacts
- Plume rise observations are extremely lacking, although satellites offer an opportunity for evaluation; modern direct observation campaigns would be very valuable
- Plume rise methods developed specifically for fire require inputs that are not typically known (i.e., heat)
- Dispersion model and meteorological errors are hard to evaluate given the uncertainties up to this point, but appear to be less critical than current errors in emissions, diurnal timing, and plume rise. Characterizing the source term for fire carries the highest level of uncertainty versus plume transport and dispersion, although plume chemistry has high uncertainty due to extreme variability and difficulty of implementation of mechanisms in models
- Observational campaigns need to directly address the lack of data for plume rise and diurnal profiles—this requires some "coupling" between smoke and fire behavior. It is important to understand fire behavior as it relates to smoke production and the scale at which current and future operation models will function. Simple fire behavior is not the main issue of concern—persistence of fire is fine during the fire-equilibrium state—concern arises when the fire is outside this state (small or large) and when the issue for smoke is focused on complex and highly variable cases

5.4 Suggestions for the Future

- We believe SEMIP, or something like SEMIP, should be continued into the future, in order to establish and maintain baseline comparison test cases and to ensure that standard comparisons between models and model validations needed by users of the models are done on a regular basis (as models are updated, etc.).

- To do so, there should probably be an invested structure (e.g., a small scientific advisory committee) chartered to be responsive to requests/comments from the larger scientific and management communities. This group would maintain and approve the test cases to be maintained and would advise the JFSP Board on critical needs.
- Future work can be divided into two areas: (1) data/test case maintenance, and (2) continued model comparisons/evaluations.
- Data/test case maintenance would include collecting new datasets, ensuring dataset quality and availability, and, if existing archives (e.g., the U.S. Forest Service Data Archive) are not capable of containing all of the needed ancillary data to maintain a test case, maintaining some sort of dataset server. Potential data maintenance costs would depend highly on the ability of existing data archives to absorb these datasets without additional costs, and on any data assurance / data quality requirements imposed on researchers before data can be submitted to be archived.
- Continued model comparisons/evaluation would minimally need to be targeted model runs where new versions of models and/or new models are run through a series of test cases to establish where they fit into overall model performance. Some targetable funding might be useful to enable the most urgent comparisons, with larger efforts done through the standard JFSP RFA process. Note that the specific researchers receiving this funding might vary depending on the needed research, as directed by the oversight board.
- New observation campaigns should be created with test case development and targeted towards areas of limited understanding. While the area of limited understanding may be at one modeling step, such as plume rise, for the test case to be complete data would have to be collected at all modeling steps.

APPENDIX A: SEMIP DATA WAREHOUSE

A.1 SEMIP Data Warehouse Goals and Development

As part of SEMIP: Phase 1, a data warehouse was developed to allow for community sharing of datasets. The need for a data warehouse was evident from the initial surveys done by SEMIP examining the quantity of data readily available (see Section 2.3). The goal of creating a data warehouse was to enable datasets to be easily found and shared in order to foster model development and evaluation.

The SEMIP Data Warehouse was created to be a system to collect and share of data. The goals of the SEMIP Data Warehouse were to be:

- Web-based and open access
- Easily searchable by keyword, location, time, and type of data
- Easily expandable and customizable

Other requirements were that the data warehouse have no size limits on data to be stored there; this requirement allows for multi-gigabyte meteorological databases. An additional need is that the data warehouse use simple metadata to describe the datasets within the warehouse. Later warehouse development has added a bulk upload application, which allows for data to be quickly uploaded to the warehouse through a simple Excel-type spreadsheet form (comma separated value format).

Data placed in the SEMIP Data Warehouse are assumed to be quality controlled / quality assured by the data provider. In this way, the SEMIP Data Warehouse is designed to enable part—the data accessibility part—but not all of the data sharing chain (Figure A1).

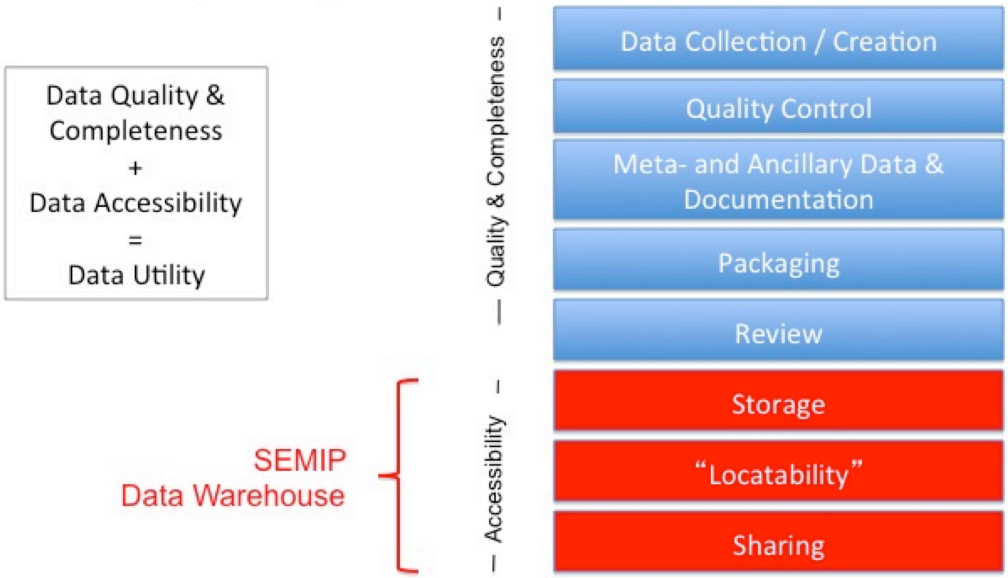
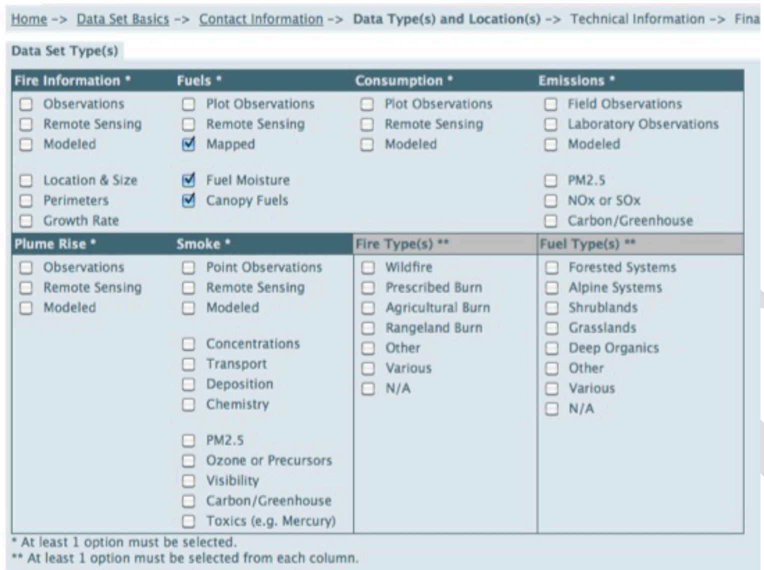


Figure A1. Data sharing and the SEMIP Data Warehouse.

A.2 SEMIP Data Warehouse Functionality

The SEMIP Data Warehouse is web-based and accessible and searchable from any standard web browser. It uses a static list of key words that users can select for both data entry and searching. Additional key words can be added as needed by system administrators, and the interface easily adjusted to match. The key words are grouped on screen to enable users to easily find specific types of data, methods of data collection, variables and outputs, etc. (Figure A2). Additionally, users can specify the location, time range, and vertical extent of the data they are interested in finding (Figure A3). The goal of the interface is to allow users to quickly and accurately identify any datasets of interest, and then to allow users to quickly see additional information about each matching dataset to determine whether they need to examine it more thoroughly.


Home -> Data Set Basics -> Contact Information -> Data Type(s) and Location(s) -> Technical Information -> Fina

Data Set Type(s)

Fire Information *	Fuels *	Consumption *	Emissions *
☐ Observations	☐ Plot Observations	☐ Plot Observations	☐ Field Observations
☐ Remote Sensing	☐ Remote Sensing	☐ Remote Sensing	☐ Laboratory Observations
☐ Modeled	☑ Mapped	☐ Modeled	☐ Modeled
☐ Location & Size	☑ Fuel Moisture		☐ PM2.5
☐ Perimeters	☑ Canopy Fuels		☐ NOx or SOx
☐ Growth Rate			☐ Carbon/Greenhouse

Plume Rise *	Smoke *	Fire Type(s) **	Fuel Type(s) **
☐ Observations	☐ Point Observations	☐ Wildfire	☐ Forested Systems
☐ Remote Sensing	☐ Remote Sensing	☐ Prescribed Burn	☐ Alpine Systems
☐ Modeled	☐ Modeled	☐ Agricultural Burn	☐ Shrublands
	☐ Concentrations	☐ Rangeland Burn	☐ Grasslands
	☐ Transport	☐ Other	☐ Deep Organics
	☐ Deposition	☐ Various	☐ Other
	☐ Chemistry	☐ N/A	☐ Various
	☐ PM2.5		☐ N/A
	☐ Ozone or Precursors		
	☐ Visibility		
	☐ Carbon/Greenhouse		
	☐ Toxics (e.g. Mercury)		

* At least 1 option must be selected.
** At least 1 option must be selected from each column.

Figure A2. Screenshot of the keyword entry form. Keywords are grouped by type of information. One or more keywords can be entered in each area. Information on fire type and fuel type are required.

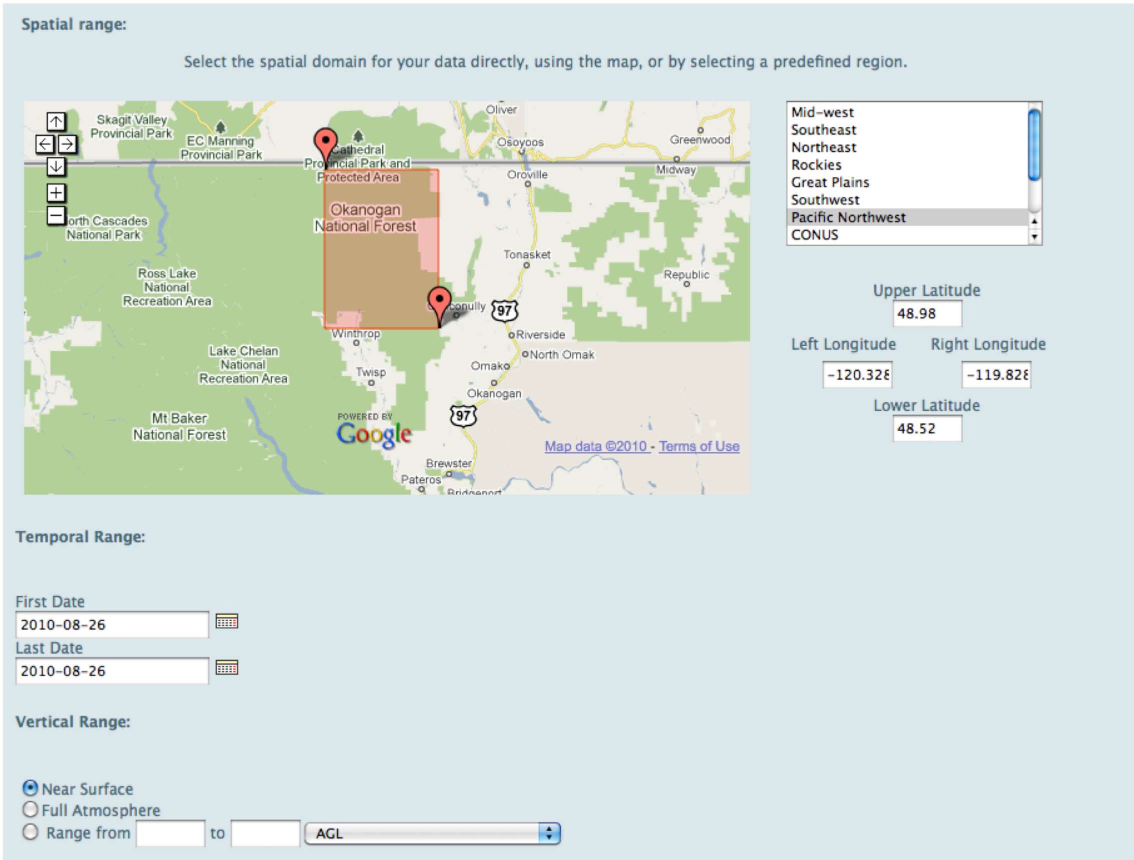


Figure A3. Screenshot of the spatio-temporal range entry form. Data is bounded by latitude and longitude, a vertical extent, and date range.

A.3 SEMIP Data Sharing Agreement

One of the major stumbling blocks to sharing data, as identified through discussions with researchers, is the fear of:

- Data misuse
- Ability to obtain credit for data used
- Capability to embargo public data use until publications are accepted

The SEMIP Data Warehouse attempted to tackle these issues through a data sharing agreement that would be required by each user trying to download data through the Data Warehouse. The data sharing agreement reads:

In obtaining data from SEMIP,

I understand that this data is provided without warrantees or guarantees as to accuracy and that any use is at my own risk. Additionally I agree to give proper accreditation in any use of the data, including properly referencing the source of the data. This includes offering the creators of the data used an opportunity to review for errors and comment *upon any analyses done, while the potential for to participate as a co-author on any peer-reviewed publications produced using the data. I further agree to abide by the SEMIP Fair Use Data Policy when utilizing the data, and not to share the raw data with others outside my project.*

In submitting data to SEMIP,

I assert that I have the legal right to share this data with SEMIP. I further agree to the storage of this data on servers and in the SEMIP data warehouse with no guarantee of security. I understand that my data may be stored on government computers that may be subject to subpoenas under the Freedom of Information Act. I agree to the use of this data in SEMIP analyses, including statistical analyses and comparisons, provided that I be given an opportunity to comment on said analyses and comparisons and review them for errors. I also assent to the display of these analyses, including selected graphics and tables based on raw data, on the SEMIP website and the dissemination of analysis results in various forms including as peer-reviewed literature and through electronic media. I understand that I will be given the opportunity to review for errors and comment upon any analyses done, and the potential to participate as a co-author on any peer-reviewed publications produced using my data.

I understand that I may choose to allow for the dissemination of my data through the SEMIP data warehouse to other researchers and users who have agreed to the SEMIP Fair Use Data Policy. I understand that my raw data will not be knowingly shared without my permission.

We believe that such an agreement would substantially lower the barriers to data sharing. However, without a broad community agreement or organization to enforce such an agreement, it is unlikely that such a system will work. One possibility is for the JFSP or alternate organization in charge of a SEMIP-like data warehouse to institute such an agreement if it is deemed useful to the community; however, a single project cannot unilaterally impose such an action.

APPENDIX B: TEST CASE DETAILS

This appendix details the test cases utilized by SEMIP to date. The test cases used by SEMIP are described in the following sub-sections, including a background description, why it was chosen, and the modeling steps the test case was used for in the SEMIP analyses. Time and space scales are noted as well the input required, output notes, and any references that were produced that include these test cases.

The test cases are:

1. **Fires Everywhere;**
2. **2008 National Emissions Inventory (NEI);**
3. **2007/2008 Regional California Wildfires (Cal);**
4. **2006 Tripod Wildfire Complex (Tripod);**
5. **2007 Georgia Bay/Bugaboo Wildfire Complex (Bugaboo);**
6. **Northwest Prescribed Burning;** [deprecated for Phase 1]
7. **Southeast Prescribed Burning;** [deprecated for Phase 1]
8. **2009 Naches Prescribed Burn (Naches);** and
9. **Multi-year Plume Case.**

B.1 Fires Everywhere

This is a non-realistic fire case that was designed to comprehensively intercompare model performance across the United States 'en masse.' This case provided a set of possible model runs for every grid cell located across the contiguous U.S. (CONUS) while retaining computational feasibility, thus providing regional as well as national information.

Multiple runs were done (one fire at a time) placing the fire sequentially at each 1 km grid cell across CONUS. For this case, a representative fire of 100 acres is used, and resulting values are reported per acre rather than per fire, as the fire occurrence is artificial. (Note: fire exists only for one day, so fire size = daily growth). The exact location of the 1 km grid matches the FCCS 1-km fuel map, and other 1-km gridded fuel maps are used through nearest neighbor association.

Primarily used for examining:

<table>
<tr><th>Modeling Steps</th><th>Output Evaluated</th><th>Notes</th></tr>
<tr><td>Fuel Loading</td><td>Total Fuel Loading
Fuel Loading by Category</td><td rowspan="2">• All values reported per acre
• Ratios between different model pathways useful
• Summaries by vegetation type useful</td></tr>
<tr><td>Total Consumption</td><td>Total Consumption
Consumption by Fire Phase
Consumption by Fuel Category</td></tr>
</table>

Time and space scales:

- CONUS, 1km grid
- Independent of time

Input data:

- Fire occurrence:
  - 100 acre fires set to occur at every grid cell on 1 km grid across CONUS but each fire modeled separately
  - 1 day with climatologically representative fuel moistures and winds for that region's dry-fire season
- Fuel Moistures used:
  - 10-hr fuel moisture: 9%
  - 1000-hr fuel moisture: 12%
  - Duff fuel moisture: 40%
- Other model settings
  - Fuel Category (Natural)
  - Percent of Canopy Biomass Consumed: 60%
  - Percent Area Blackened (Consume): 95%

Pathways evaluated to date (see Appendix C for model information):

- Fuel Loadings
  - *Fuels*
  - NFDRS 1-km
  - Hardy 1-km
  - FCCS 1-km
- Consumption
  - *Fuels > Consumption*
  - NFDRS 1-km > EPM v 1.0
  - NFDRS 1-km > FEPS v1.1
  - NFDRS 1-km > Consume v 3.0
  - NFDRS 1-km > FOFEM v 5.7
  - Hardy98 1-km > EPM v 1.0
  - Hardy98 1-km > FEPS v1.1
  - Hardy98 1-km > Consume v 3.0
  - Hardy98 1-km > FOFEM v 5.7
  - FCCS v1 1-km > EPM v 1.0
  - FCCS v1 1-km > FEPS v1.1
  - FCCS v1 1-km > Consume v 3.0
  - FCCS v1 1-km > FOFEM v 5.7

Other notes:

- Modern 30-m fuel maps are difficult to aggregate to 1-km; to compare 30-m fuels, individual fire test cases (Bugaboo, Tripod) and the large-fire National Emissions Inventory test case (NEI) were used.

- This test case may need to be updated to a 30-m grid for future comparisons.
- Future updated comparisons should continue to use climatological fuel moistures and wind values representative of that region’s fire season.

B.2 2008 National Emissions Inventory (NEI)

Due the importance (for regulatory and policy uses) of the EPA’s official triennial National Emissions Inventory (NEI), the most recent NEI year (2008) was selected as a test case. Results from this test case are intended to directly inform questions of uncertainties and implications of model choices on the overall values computed for the NEI.

The large fire inventory from the MTBS was used for much of the NEI test case work in Fuel Loading, Total Consumption, and Emissions. This is a subset of the full fire inventory for 2008, but provides a consistent set of fire perimeters with which to work.

Primarily used for examining:

Modeling Steps	Output Evaluated	Notes
Fire Information	Total Burned Area Total Burned Area by Fire Type	• Used to examine coarse- and high-resolution fuel databases and their aggregate effects over a year • Most analyses done for large-fires only (based on MTBS) in order to provide consistent fire perimeters
Fuel Loading	Total Fuel Loading Fuel Loading by Category	
Consumption	Total Consumption Consumption by Fire Phase Consumption by Fuel Category	
Emissions	Total Emissions by Species Total Emissions by Species per Fire Phase	
Dispersion	(not done for Phase 1)	

Time and space scales:

- CONUS, grid scales from 30-m up
- 2008 fires, with daily information

Input data:

- Fire occurrence for large-fire subset:
  - MTBS perimeters equal to or over 500 acres in the eastern U.S. and 1000 acres in the western U.S.
  - Fire perimeters intersected with fuel loading maps and then aggregated for evaluation
- Fuel moistures used:
  - Regional fuel moistures were based on the WFAS 1000-hr fuel moisture maps from WFAS. Based on when fires in a region occurred and the WFAS maps, the following regional values were identified and utilized:

FCCS_REGION	10 hr Fuel Moisture	1000 hr Fuel Moisture	Duff Moisture
Pacific Northwest	6	8	25
Sierra Nevada	6	8	25
Rocky Mountain and Central U.S.	8	12	40
Southwest	6	8	25
Northeast	12	22	150
Southeast	12	22	150

- Other model settings
  - Fuel Category (Natural)
  - Percent of Canopy Biomass Consumed: 60%
  - Percent Area Blackened (Consume): 95%

Pathways evaluated to date (see Appendix C for model information):

- Fire Information (all fires)
  - *Fire Information*
  - SmartFire v2 / NEI method (ICS-209, HMS, MTBS)
- Fuel Loadings (MTBS fires only)
  - *Fuels*
  - FCCS v1 1-km
  - FCCS-LF 1-km
  - FCCS-LF 30-m
  - LANDFIRE 30-m
  - FINN
  - FLAMBE
- Consumption (MTBS fires only)
  - *Fuels > Consumption*
  - FCCS v1 1-km > Consume v4.0
  - FCCS v1 1-km > FOFEM v 5.7
  - FCCS-LF 1-km > Consume v4.0
  - FCCS-LF 1-km > FOFEM v 5.7
  - FCCS-LF 30-m > Consume v4.0
  - FCCS-LF 30-m > FOFEM v 5.7
  - LANDFIRE 30-m > Consume v4.0
  - LANDFIRE 30-m > FOFEM v 5.7
  - FINN > FINN
  - FLAMBE > FLAMBE

- Emissions (MTBS fires only)
    - *Fuels > Consumption > Emissions*
    - FCCS v1 1-km > Consume v4.0 > Consume v4.0
    - FCCS v1 1-km > FOFEM v 5.7 > FOFEM v 5.7
    - FCCS-LF 1-km > Consume v4.0 > Consume v4.0
    - FCCS-LF 1-km > FOFEM v 5.7 > FOFEM v 5.7
    - FCCS-LF 30-m > Consume v4.0 > Consume v4.0
    - FCCS-LF 30-m > FOFEM v 5.7 > FOFEM v 5.7
    - LANDFIRE 30-m > Consume v4.0 > Consume v4.0
    - LANDFIRE 30-m > FOFEM v 5.7 > FOFEM v 5.7
    - FINN > FINN > FINN
    - FLAMBE > FLAMBE > FLAMBE

Other notes:

- Information on smaller fires collected for the 2011 National Emissions Inventory (currently underway) may mean that this test case should be changed to be 2011, not 2008, for future work.

B.3 2007/2008 California Wildfires (Cal)

The 2007 and 2008 California wildfires were selected to include a test case where regional wildfire activity was ongoing. Both of these wildfire events included multiple significant fires occurring simultaneously. This test case contains two distinct periods:

- 10/19-11/9/2007 centered over Southern California when the Witch, Branch, Buckweed, Harris, and other fires were occurring.
- 6/21-10/25/2008 centered over Northern California when what is now known as the Lightning Series fire event was ongoing. This event included over 2,780 individual fires, sparked by lightning, which coalesced to several large fires including the Klamath Theater fire complex.

The two periods are included because they provide similar regional wildfire occurrence but with distinct and contrasting conditions. The 2007 fires were contained primarily in the region of the Los Angeles-San Diego corridor, while in 2008 fires occurred north of Sacramento. In both time periods, significant smoke impacts were observed at population centers in California and smoke travelled to neighboring states.

Primarily used for examining:

Modeling Steps	Output Evaluated	Notes
Dispersion	Surface $PM_{2.5}$ Concentrations	• Test case covers the region over the fires and did not extend into neighboring states.

Time and space scales:

- Regional (California); 36 km grid scale from the modeled meteorological data
- Month to multi-month episodes, daily and hourly information available

Input data:

- Fuel Moistures:
    - Default static values, described as 9% for 10-hr fuel moisture for all fires; 12% for 1000-hr fuel moisture for wildfires and WFUs; and 25% for 1000-hr fuel moisture for prescribed burns and fires of unknown type.
- Meteorological data:
    - The Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model, Version 5 (MM5) v 3.7 (Grell et al., 1994)
    - Initial and boundary meteorological conditions obtained from the National Centers for Environmental Prediction (NCEP) North American Mesoscale (NAM) model 40 km forecast product (Janjic, 2003).
- Other model settings:
    - Anthropogenic emissions were taken from the 2002 U.S. Environmental Protection Agency (US EPA) National Emissions Inventory v 3 (U.S. EPA, 2006) and projected from the NEI to the current year using the Economic Growth Analysis System (EGAS) v4.0 (Bollman and Stella, 2001).
    - Mobile emissions were generated using MOBILE6 (U.S. EPA, 2003)
    - Biogenic emissions were generated using the Biogenic Emissions Inventory System (BEIS) v 3.09 (Vukovich and Pierce, 2002).
    - Sparse Matrix Operator Kernel Emissions (SMOKE) v2.3 processing system (Houyoux et al., 2000; Houyoux and Adelman, 2001) was used to process all emissions

Observational datasets

- AirNow Surface $PM_{2.5}$ concentrations (2007)
- USDA Forest Service deployed monitors $PM_{2.5}$ concentrations (2008)

Pathways evaluated to date (see Appendix C for model information):

- Modeled smoke predictions from the BlueSky Gateway system were analyzed. BlueSky Gateway uses the pathway:

    Fire info > Fuels > Consumption > Time Profile > Emissions >
    ... Plume Rise > Dispersion

    SmartFire v1 real-time > FCCS v1 > Consume v3 > FEPS v1 > WRAP >
    … FEPS v1 > CMAQ

Other notes:

- The BlueSky Gateway is a daily prediction system that estimates $PM_{2.5}$ concentrations across CONUS.
- Strand et al. (2012) contains further details on models used and the case study.

B.4 2006 Tripod Wildfire Complex (Tripod)

Tripod provides a singular wildfire complex test case in the Western United States. It burned over 175,000 acres from late July until the end of October 2006 in the Okanogan-Wenatchee National Forest in Washington State. The specific dates are:

- 7/24-10/31/2006

It was notable for its location in rugged terrain and potential for smoke plumes to drain downslope into communities located down-valley from the fire.

Tripod has been a focal point for fire research projects, including a custom FCCS fuelbed map created by the Okanogan-Wenatchee Forest at 25-m resolution. Several $PM_{2.5}$ monitors were deployed by the USDA Forest Service downwind of the fire in a widely spaced network covering north-central and northeastern Washington State. The monitors continuously collected data from early August through mid-October 2006 (Strand et al., 2011). Other studies include an assessment of fuels treatment effectiveness (Pritchard et al. 2010), an evaluation of MTBS burn severities (Newcomer et al. 2009), and an assessment of fuels treatment influences on carbon flux (Justice et al. 2010).

Primarily used for examining:

Modeling Steps	Output Evaluated	Notes
Fire Information	Total Burned Area	• $PM_{2.5}$ Observation data near the fire is available for analyses of dispersion
Fuel Loading	Total Fuel Loading Fuel Loading by Fuel Category	
Consumption	Total Consumption Consumption by Fuel Category	
Emissions	Total Emissions by Species	
Plume Rise	(not completed for Phase 1)	
Dispersion	(not completed for Phase 1)	

Time and space scales:

- fire dimensions: approximately 175,000 acres ranging from 58 km North-South, 31 km East-West
- Latitude range: 48.453 to 48.995 and Longitude range: -120.15 to -119.821
- 25-m to 1-km gridded fuels
- 10s to 100s of kilometers smoke impacts
- daily fire information available
- hourly smoke concentration observations available

Input data:

- Fire information from various sources evaluated
- For Fuel Loading, Consumption, Emissions calculations, MTBS fire perimeters were used

- Fuel Moistures were developed from WFAS and used for Consumption and Emissions calculations as:
    - 10-hr Fuel Moisture (FOFEM): 6%
    - 1000-hr Fuel Moisture: 8%
    - Duff Fuel Moisture: 25%
- Other Consumption Model Settings for Consumption and Emissions calculations:
    - Preburn Fuel Loading (Section 4.1)
    - Fuel Category (Natural)
    - Ecoregion (Consume: Western; FOFEM: PacificWest)
    - Season (FOFEM:summer)
    - Percent of Canopy Biomass Consumed: 60%
    - Percent Area Blackened (Consume): 95%
- 4-km and 12-km regional meteorological model data collected

Pathways evaluated to date (see Appendix C for model information):

- Fire Information
    - *Fire Information*
    - GeoMAC Perimeters
    - MTBS Perimeters
    - SmartFire v1
    - MODIS Active Detects
    - MODIS Burn Scars

- Fuel Loadings (using MTBS perimeter)
    - *Fuels*
    - NFDRS 1-km
    - Hardy98 1-km
    - FCCS v1 1-km
    - FCCS-LF 1-km
    - FCCS-LF 30-m
    - LANDFIRE 30-m
    - Ok-Wen 25-m

- Consumption (using MTBS perimeter)
    - *Fuels > Consumption*
    - NFDRS 1-km > Consume v 4.0
    - NFDRS 1-km > FOFEM v 5.7
    - Hardy98 1-km > Consume v 4.0
    - Hardy98 1-km > FOFEM v 5.7
    - FCCS v1 1-km > Consume v 4.0
    - FCCS v1 1-km > FOFEM v 5.7
    - FCCS-LF 1-km > Consume v 4.0
    - FCCS-LF 1-km > FOFEM v 5.7
    - FCCS-LF 30-m > Consume v 4.0
    - FCCS-LF 30-m > FOFEM v 5.7
    - LANDFIRE 30-m > Consume v 4.0

- LANDFIRE 30-m > FOFEM v 5.7
- Ok-Wen 25-m > Consume v 4.0
- Ok-Wen 25-m > FOFEM v 5.7

- Emissions (using MTBS perimeter)
  - *Fuels > Consumption > Emissions*
  - NFDRS 1-km > Consume v4.0 > Consume v4.0
  - NFDRS 1-km > FOFEM v 5.7 > FOFEM v 5.7
  - Hardy98 1-km > Consume v4.0 > Consume v4.0
  - Hardy98 1-km > FOFEM v 5.7 > FOFEM v 5.7
  - FCCS v1 1-km > Consume v4.0 > Consume v4.0
  - FCCS v1 1-km > FOFEM v 5.7 > FOFEM v 5.7
  - FCCS-LF 1-km > Consume v4.0 > Consume v4.0
  - FCCS-LF 1-km > FOFEM v 5.7 > FOFEM v 5.7
  - FCCS-LF 30-m > Consume v4.0 > Consume v4.0
  - FCCS-LF 30-m > FOFEM v 5.7 > FOFEM v 5.7
  - LANDFIRE 30-m > Consume v 4.0 > Consume v 4.0
  - LANDFIRE 30-m > FOFEM v 5.7 > FOFEM v 5.7
  - Ok-Wen 25-m > Consume v 4.0 > Consume v 4.0
  - Ok-Wen 25-m > FOFEM v 5.7 > FOFEM v 5.7

Other notes:

- Fires in British Columbia and eastern Oregon ongoing at the same time may interfere with evaluation of results with respect to observations; caution should be used at the plume rise and dispersion levels

B.5 2007 Bugaboo Wildfire Complex (Bugaboo)

The Bugaboo fire was selected because it was a singular wildfire complex in the Eastern United States. This wildfire burned in areas with deep organic duff layers and therefore provides a test case with a complex fuel bed. The Bugaboo wildfire complex lasted for many weeks. Specific dates are:

- 4/16-6/18, 2007

Bugaboo (also known as the Georgia Bay Fire complex) burned in eastern Georgia and western Florida. For this case all fires that became associated with the complex are used in the analyses, even for periods when they were separate. During this wildfire, smoke impacts were felt in population centers across the southeastern U.S.

Primarily used for examining:

Modeling Steps	Output Evaluated	Notes
Fire Information	Total Burned Area	• $PM_{2.5}$ data collected in the cities nearby (AirNowTech) can be used at the dispersion level
Fuel Loading	Total Fuel Loading Fuel Loading by Fuel Category	
Consumption	Total Consumption Consumption by Fuel Category	
Emissions	Total Emissions by Species	
Plume Rise	(not completed for Phase 1)	
Dispersion	(not completed for Phase 1)	

Time and space scales:

- fire dimensions: approximately 563,000 acres measuring 94 km North-South, 47 km East-West
- Latitude range: 30.355 to 31.205
- Longitude range: -82.608 to -82.133
- 30-m to 1-km gridded fuels
- 10s to 100s of kilometers smoke impacts
- daily fire information available
- hourly smoke concentration observations available

Input data:

- Fire information from various sources evaluated
- For Fuel Loading, Consumption, Emissions calculations used MTBS fire perimeters
- Fuel Moistures were developed from WFAS and used for Consumption and Emissions calculations:
    - 10-hr Fuel Moisture (FOFEM): 8%
    - 1000-hr Fuel Moisture: 12%
    - Duff Fuel Moisture: 40%
- Other Consumption Model Settings for Consumption and Emissions calculations:
    - Preburn Fuel Loading (Section 4.1)
    - Fuel Category (Natural)
    - Ecoregion (Consume: Southern; FOFEM: SouthEast)
    - Season (FOFEM:summer)
    - Percent of Canopy Biomass Consumed: 60%
    - Percent Area Blackened (Consume): 95%

Pathways evaluated to date (see Appendix C for model information):

- Fire Information
    - *Fire Information*
    - MTBS perimeter

- Fuel Loadings (using MTBS perimeter)
    - *Fuels*
    - NFDRS 1-km

    - FCCS v1 1-km
    - FCCS-LF 1-km
    - FCCS-LF 30-m
    - LANDFIRE 30-m

- Consumption (using MTBS perimeter)
    - *Fuels > Consumption*
    - NFDRS 1-km > Consume v 4.0
    - NFDRS 1-km > FOFEM v 5.7
    - FCCS v1 1-km > Consume v 4.0
    - FCCS v1 1-km > FOFEM v 5.7
    - FCCS-LF 1-km > Consume v 4.0
    - FCCS-LF 1-km > FOFEM v 5.7
    - FCCS-LF 30-m > Consume v 4.0
    - FCCS-LF 30-m > FOFEM v 5.7
    - LANDFIRE 30-m > Consume v 4.0
    - LANDFIRE 30-m > FOFEM v 5.7

- Emissions (using MTBS perimeter)
    - *Fuels > Consumption > Emissions*
    - NFDRS 1-km > Consume v4.0 > Consume v4.0
    - NFDRS 1-km > FOFEM v 5.7 > FOFEM v 5.7
    - FCCS v1 1-km > Consume v4.0 > Consume v4.0
    - FCCS v1 1-km > FOFEM v 5.7 > FOFEM v 5.7
    - FCCS-LF 1-km > Consume v4.0 > Consume v4.0
    - FCCS-LF 1-km > FOFEM v 5.7 > FOFEM v 5.7
    - FCCS-LF 30-m > Consume v4.0 > Consume v4.0
    - FCCS-LF 30-m > FOFEM v 5.7 > FOFEM v 5.7
    - LANDFIRE 30-m > Consume v 4.0 > Consume v 4.0
    - LANDFIRE 30-m > FOFEM v 5.7 > FOFEM v 5.7

Other notes:

- Background regional air quality may not be ‘clean’ given the location of the fire and urban centers within the region. This is important to consider if relative impact of fire is analyzed.

B.6 Northwest Prescribed Burning [deprecated for Phase 1]

Northwest prescribed burning was identified as a western regional prescribed fire test case with multiple prescribed burns occurring simultaneously. The goal of this case is to collect information for an entire season. This test case was deprecated for Phase 1 in order to focus on other cases.

Information is currently undergoing collection as part of the 2011 EPA National Emissions Inventory that may serve as the basis for a useful future test case for this region.

Primarily used for:

Modeling Steps	Output Evaluated	Notes
Fire Information	(deprecated for Phase 1)	• (deprecated for Phase 1)
Fuel Loading	(deprecated for Phase 1)	
Consumption	(deprecated for Phase 1)	
Emissions	(deprecated for Phase 1)	
Plume Rise	(deprecated for Phase 1)	
Dispersion	(deprecated for Phase 1)	

B.7 Southeast Prescribed Burning [deprecated for Phase 1]

Southeast prescribed burning was identified as an eastern regional prescribed fire test case with multiple prescribed burns occurring simultaneously. The goal of this case is to collect information for an entire season. This test case was deprecated for Phase 1 in order to focus on other cases.

Information is currently undergoing collection as part of the 2011 EPA National Emissions Inventory that may serve as the basis for a useful future test case for this region.

Primarily used for:

Modeling Steps	Output Evaluated	Notes
Fire Information	(deprecated for Phase 1)	• (deprecated for Phase 1)
Fuel Loading	(deprecated for Phase 1)	
Consumption	(deprecated for Phase 1)	
Emissions	(deprecated for Phase 1)	
Plume Rise	(deprecated for Phase 1)	
Dispersion	(deprecated for Phase 1)	

B.8 2009 Naches Prescribed Fire (Naches)

The Naches, Washington, prescribed burn was selected as a single case to examine system sensitivity of each modeling step, from fire information to plume rise. This sensitivity is quantified across time and space in terms of how the surface $PM_{2.5}$ concentrations (i.e., the Dispersion Modeling Step) are modified by different model choices in the previous modeling steps.

The Naches prescribed burn was conducted 9/28/2009 by the Naches Ranger District on the Okanogan-Wenatchee National Forest in south-central Washington State. Eight hundred hectares were ignited from approximately 1230 to 1530 PDT. $PM_{2.5}$ monitoring data were obtained from the nearby towns of Naches and Yakima, and hourly $PM_{2.5}$ concentrations up to 110 $\mu g/m^3$ were recorded in Yakima from 1500 to 2300 PDT by a Radiance Research nephelometer.

The Naches fire was simulated as both a prescribed fire and a wildfire. As a prescribed fire, 18 100-acre prescribed fires were simulated as beginning every 10 minutes from 1240 to 1530 PDT in order to represent the effect of the planned ignition sequence. As a wildfire, a single 3000 acre wildfire was simulated.

Primarily used for:

Modeling Steps	Output Evaluated	Notes
Fire Information	Dispersion	• Simple test case used for sensitivity studies
Fuel Loading	Dispersion	
Consumption	Dispersion	
Time Profile	Dispersion	
Emissions	Dispersion	
Plume Rise	Dispersion	

Time and space scales:

- Regional; 4-km and 1.33-km grid scale from the modeled meteorological data
- Hourly & 10-min.

Input data:

- Fire Information from the Naches Ranger District.
- Fuel Moisture – By default, fuel moistures for a prescribed fire are; 10% for 1-hr fuels, 12% for 10hr fuels, 12% for 100-hr fuels, 22% for 1000-hr fuels, 130% for live fuels and 150% for duff. For a wildfire the fuels moistures are defaulted to dryer conditions of: 5& for 1-hr fuels, 8% for 10-hr fuels, 9% for 100-hr fuels, 12% for 1000-hr fuels, 80% for live fuels, and 40% for duff.
- Meteorology – Weather Research Forecast (WRF) Model, 1.33 km resolution

Model pathways evaluated:

- Dispersion output evaluated spatially and temporally to determine sensitivity to changes in the diurnal distribution of emissions, using the following pathways:
- *Fire info > Fuels > Consumption > Time Profile >*
  … Emissions >Plume Rise > Dispersion
  Ranger district info > FCCS-LF 1-km > CONSUME v4.0 > FEPS v1.1 >
  … FEPS v1.1 > FEPS v1.1 > HYSPLIT
- Variations used to test sensitivity of dispersion results to previous steps are:
    - Fire Info: prescribed fire, wildfire
    - Fuels: 50%, 80%, 100%, 125%, 200%
    - Consumption: 50%, 80%, 100%, 125%, 200%
    - Time Profile: 10 variants (see Appendix D.4)
    - Emissions: 50%, 80%, 100%, 125%, 200%
    - Plume Rise: 50%, 80%, 100%, 125%, 200%

B.9 Multi-year Plume Case

The purpose of this test case was to examine matches of wildfire smoke plumes with satellite data over multiple years. This was done to take advantage of observed plumes under modern satellite products. Work for Phase 1 has focused on plume height tops, but work on total column smoke is also possible.

Primarily used for:

Modeling Steps	Output Evaluated	Notes
Plume Rise	Plume Top Height	• Satellite-derived observations of fire plumes vs. real-time forecast modeling of plumes
Total Column Smoke	(not done for Phase 1)	

Time and space scales:

- Work done for Phase 1 used data from 2006 through 2008
- Individual plumes as observed by satellites
- Satellite observations are instantaneous overpass measurements
- Modeled plumes are hourly data

Input data:

- CALIPSO-derived plume tops
- MISR wind corrected median plume top heights
- FEPS modeled plume heights from real-time BlueSky Gateway forecast system
- Fuel Moistures:
    - Default static values, described as 9% for 10-hr fuel moisture for all fires; 12% for 1000-hr fuel moisture for wildfires and WFUs; and 25% for 1000-hr fuel moisture for prescribed burns and fires of unknown type.
- Meteorological data:
    - The Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model, Version 5 (MM5) v3.7 (Grell et al., 1994)
    - Initial and boundary meteorological conditions obtained from the National Centers for Environmental Prediction (NCEP) North American Mesoscale (NAM) model 40 km forecast product (Janjic, 2003).

Model pathways evaluated:

- Plume heights from real-time forecast system using:
  Fire info > Fuels > Consumption > Time Profile >
  ... Emissions > Plume Rise > Dispersion
  SmartFire v1 real-time > FCCS v1 > Consume 3.0 > WRAP >
  … FEPS v1 > FEPS v1 > CMAQ

Other notes:

- The BlueSky Gateway is a daily prediction system that estimates $PM_{2.5}$ concentrations across CONUS.

APPENDIX C: MODELS, DATASETS, AND ANALYSIS TOOLS USED

This appendix details the models, datasets, and software frameworks/platforms/analysis tools used in SEMIP. Descriptions are intended to both give background information and provide enough detail to replicate the results of SEMIP.

Note: Sources of data are given to document where the original data were obtained. Where possible, datasets used in SEMIP have been placed in the SEMIP Data Warehouse for future use and access.

C.1 FIRE INFORMATION

Note: Fire information was generally processed through the SmartFire V2 fire information platform; see C.7.2 for more information.

C.1.1 MODIS Active Detects: Moderate Resolution Imaging Spectroradiometer (MODIS) Thermal Anomalies

MODIS Thermal Anomalies/Fire products (MCD14ML) are primarily derived from MODIS 4- and 11-micrometer radiances. The fire detection strategy is based on absolute detection of a fire (when the fire strength is sufficient to detect), and on detection relative to its background (to account for variability of the surface temperature and reflection by sunlight). The product includes fire occurrence (day/night), fire location, the logical detection confidence, and fire radiative power. The Terra MODIS instrument acquires data twice daily (10:30 AM and PM), as does the Aqua MODIS (1:30 PM and AM). MODIS active fire detects were acquired from the cumulative databases provided by the USFS Remote Sensing Applications Center.

Source:

- Obtained via http://activefiremaps.fs.fed.us/gisdata.php on 7/14/2009
- Algorithm version: MCD14ML, Collection 5, Version 1
- Individual download example: http://activefiremaps.fs.fed.us/data/fireptdata/mcd14ml_2006_005_01_conus_shp.zip

References:

- File metadata page example: http://activefiremaps.fs.fed.us/data/fireptdata/mcd14ml_2006_conus.htm
- Giglio, L., Csiszar, I., Justice, C.O. 2006. Global distribution and seasonality of active fires as observed with the Terra and Aqua MODIS sensors. *Journal of Geophysical Research - Biogeosciences*, Vol 111, G02016, doi:10.1029/2005JG000142.

C.1.2 ICS-209 Reports: Incident Command Summary Reports

The ICS-209 incident report is a form produced by incident command during or after fires for which there was a federal response – primarily, but not exclusively, large fires. The report includes many fields useful for incident command and logistics, including information on fire location and size. The ICS-209 is not a spatial product; the only geographic information provided is a set of coordinates that indicate the fire ignition point. Spatial data needs to be incorporated from other sources. On large incidents, ICS-209 reports are often produced daily or twice daily during the active portion of the fire; however, some smaller incidents are recorded by only a single ICS-209 report well after the fire has completed.

Source:

- Obtained via http://fam.nwcg.gov/fam-web/sit/sit_YYYY.exe (where YYYY is the calendar year) on 7/14/2009

References:

- Blank ICS-209 form: https://fam.nwcg.gov/fam-web/sit/
- Historical incidents: http://fam.nwcg.gov/fam-web/hist_209/report_list_209

C.1.3 MTBS Perimeters: Monitoring Trends in Burn Severity Project Polygons

The Monitoring Trends in Burn Severity (MTBS) project assesses the frequency, extent, and magnitude (size and severity) of all large wildland fires (includes wildfire, wildland fire use, and prescribed fire) in the conterminous United States (CONUS), Alaska, Hawaii, and Puerto Rico for the period of 1984 through 2010 at present. All fires reported as greater than 1,000 acres in the western U.S. and greater than 500 acres in the eastern U.S. are mapped across all ownerships. MTBS produces a series of geospatial and tabular data for analysis at a range of spatial, temporal, and thematic scales and are intended to meet a variety of information needs that require consistent data about fire effects. Burn severity and fire perimeter maps are produced by assessing pre- and post-fire 30 meter resolution USGS Landsat Thematic Mapper imagery.

Source:

- MTBS fire perimeters and burn severity rasters acquired via http://www.mtbs.gov/nationalregional/intro.html on 4/17/2009.

References:

- Eidenshink, J., Schwind, B., Brewer, K., Zhu, Z., Quayle, B., Howard, S. 2007. A project for monitoring trends in burn severity. *Fire Ecology*. Vol 3, No 1.

C.1.4 NOAA HMS: National Oceanic and Atmospheric Administration (NOAA) Hazard Mapping System (HMS) Fire Product

The HMS fire product, developed by NOAA in 2001, combines automated detections from the Fire Identification, Mapping, and Monitoring Algorithm (FIMMA), the Wildfire Automated Biomass Burning Algorithm (WF-ABBA) and the MOD14 algorithms. Algorithms are applied to GOES-East and -West, MODIS Aqua and Terra, and the AVHRR instrument on available NOAA polar orbiting satellites, of which there are as many as four operational at a time. Analysts quality control the automated detections, manually deleting those locations that are felt to be false detects (power plants or other industrial sites, reflective cloud edges, surface heat islands, etc.) and adding detects that the algorithms have not identified. Detected fires from all algorithms are reconciled onto a 1 km spatial grid.

Source:

- HMS fire product acquired via http://satepsanone.nesdis.noaa.gov/FIRE/fire.html on a daily basis between 1/1/2003 and 12/31/2011.

References:

- Schroeder, W., Prins, E., Giglio, L., Csiszar, I., Schimdt, C., Morisette, J., Morton, D. 2008. Validation of GOES and MODIS active fire detection products using ASTER and ETM+ data. *Remote Sens. Environ.*, 112, 2711-2726.
- Ruminski M., Kondragunta S., Draxler R. R., and Zeng J. 2006. Recent changes to the Hazard Mapping System. *15th International Emission Inventory Conference*, New Orleans, LA.

C.1.5 MODIS Burn Scars: Moderate Resolution Imaging Spectroradiometer (MODIS) MCD41 Burned Area Product

The MODIS burned area product (MCD41) uses the temporal pattern of observed surface reflectance to detect areas of rapid change that may be caused by fire. An estimate of the date of burning (with an eight day precision) is also provided. MCD41 is produced on a 500 m spatial resolution. Daily predicted reflectances are developed using recent historical reflectance observations and a bi-directional reflectance model. Large discrepancies between predicted a measured reflectances are attributed to surface changes.

Source:

- MODIS burned area product acquired via https://wist.echo.nasa.gov/wist-bin/api/ims.cgi?mode=MAINSRCH&JS=1 on 7/21/2009.
- Data product selected: "MODIS/Terra+Aqua Burned Area Monthly L3 Global 500m SIN grid v005"

References:

- MCD45 User's Guide Version 2: http://modis-fire.umd.edu/Documents/MODIS_Burned_Area_User_Guide_2.0.pdf
- Roy, D.P., Jin, Y., Lewis, P.E., Justice, C.O. 2005. Prototyping a global algorithm for systematic fire-affected area mapping using MODIS time series data. *Remote Sensing of Environment*, 97:137-162.

C.1.6 GeoMAC Perimeters

The Geospatial Multi-Agency Coordination Group (GeoMAC) provides online access to compiled wildland fire perimeters. The perimeters are polygon shapefiles that are developed by GIS specialists working on each incident. The perimeters are based on various data sources, including infrared cameras mounted on helicopters, aircraft, or satellite and ground-based GPS units. GeoMAC perimeters are an operational product created during the incident and are thus not final or official perimeters. Multiple perimeters are often available for a single incident that can be used to estimate fire progression over time.

Source:

- Annual perimeter compilation shapefiles acquired via http://rmgsc.cr.usgs.gov/outgoing/GeoMAC/historic_fire_data/ on 7/16/2009.

References:

- GeoMAC download procedures: http://rmgsc.cr.usgs.gov/outgoing/GeoMAC/geomac_download_procedures.pdf
- GeoMAC 101 presentation: http://rmgsc.cr.usgs.gov/outgoing/GeoMAC/GeoMAC_101.pptx

C.1.8 SmartFire v1: Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation (SmartFire version 1)

SmartFire v1 is an algorithm and database system developed and built within a geographic information system (GIS) framework that combines multiple sources of fire information and reconciles them into a unified dataset. It was developed to take advantage of multiple data sources while avoiding double counting. SmartFire v1 aggregates and reconciles two datasets: ICS-209 reports and fire detects from the NOAA Hazard Mapping System (HMS). Note that SmartFire v1 uses a single reconciliation algorithm and two input datasets. The newer SmartFire v2 can use any number of input data sources and is a framework for merging fire information, rather than a single algorithm. SmartFire v1 was originally developed to support real-time predictive smoke modeling.

Source:

- SmartFire v1 data were acquired on 9/16/2009.
- SmartFire v1 data are available via Sean Raffuse of Sonoma Technology, Inc.
- Data used include annual prediction point shapefiles.

References:

- SmartFire algorithm description: http://www.getbluesky.org/smartfire/docs/SMARTFIRE_Algorithm_Description_Final.pdf

C.1.9 GOES WFABBA: Geostationary Earth Satellite (GOES) Wildfire Automated Biomass Burning Algorithm (WFABBA) Detects

GOES WFABBA is an automated fire detection product that relies on the NOAA GOES geostationary weather satellites. Because of the geostationary orbits, WFABBA fire detects are available every half hour at 4 km resolution for the western hemisphere. WFABBA relies on three spectral channels: visible, short-wave infra-red, and long-wave infra-red. Fires from the WFABBA are divided into six categories: processed fire, saturated fire pixel, cloudy fire pixel, high possibility fire pixel, medium possibility fire pixel, and low possibility fire pixel. Sources of false alarms include data noise, extremely hot surfaces, and cloud shadows.

Source:

- GOES WFABBA data were acquired from Mark Ruminski of NOAA NESDIS via personal communication on 6/11/12.
- Short-term archive (last six months) available at http://satepsanone.nesdis.noaa.gov/FIRE/fire.html.

References:

- WFABBA Algorithm description: http://wfabba.ssec.wisc.edu/algorithm.html
- Menzel, W. P., and E. M. Prins, 1996: Monitoring biomass burning with the new generation of geostationary satellites, *Biomass Burning and Global Change*, edited by J.S. Levine, 56-64, The MIT Press, Cambridge, MA.

C.2 FUELS

C.2.1 NFDRS: National Fire Danger Rating System Fire Danger Fuel Model Map

The NFDRS is a 1-km gridded map and associated look up table that provides fuel loading information for the continental United States. This map was created by Robert Burgan and others in the mid-1990s as a tool to aid in fire danger rating (Burgan et al. 1997; Burgan et al. 1998). To create the map, ground sampled data were combined with landcover data (based on the National Difference Vegetation Index (NDVI) satellite data) and the Omernick Ecoregion Map to assign NFDRS fuel models to each 1 km pixel. These maps include fuel quantity information for live woody fuels (shrubs), herbaceous fuels, and 1-, 10-, 100-, and 1000-hour downed woody fuels. The maps do not include information on larger woody fuels, decomposed (rotten) woody fuels, canopy fuels, litter, or duff.

Although this map was not originally intended to provide biomass information for modeling fuel consumed and smoke emitted due to landscape burning many smoke emissions modelers have taken advantage of the nationwide coverage of this map layer to estimate smoke. The NFDRS fuels map was used in the SEMIP analyses because it has been used in various studies for computing fire emissions despite the lack of information for heavy woody fuels, litter, and duff.

Source:

- Cohen, J. D. and Deeming, J. E. (1985) The National Fire Danger Rating System: Basic Equations. US Department of Agriculture, Pacific Southwest Forest and Range Experiment Station, General Technical Report PSW-82. http://www.fs.fed.us/psw/publications/documents/psw_gtr082/psw_gtr082.pdf

References:

- Burgan, R.E., Hardy, C.C., Ohlen, D.O., Fosnight, G. 1997. Landcover Ground Sample Data. Ogden UT: USDA Forest Service Intermountain Research Station, Gen Tech Rep INT-GTR-368CD
- Burgan RE, Klaver RW, Klaver JM 1998. Fuel models and fi re potential from satellite and surface observations. IJWF 8:159–170

C.2.2 Hardy98: Hardy et al. 1998 Vegetation Cover and Fuel Loading Map

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. The map and associated fuels data that has become known as Hardy98 was produced by members of the Fire Modeling Institute at the USDA Forest Service Fire lab in Missoula, Montana (Hardy et al. 1998). The vegetation and fuels data in the Hardy98 fuel loading map were developed for the Western States Air Resources Council (WESTAR) to serve as input data for an air quality prediction system designed to predict smoke emissions from prescribed fire or wildfire in the western United States (Hardy et al. 1998). In this map, vegetation cover types are comprised of eighteen broad vegetation cover types created using an EROS Data Center LAND Characterization Class product. The fuel loading information linked to each vegetation cover type is derived from two photoseries publications (PNW-GTR-105 and PNW-GTR-52). While the Hardy98 fuel loading map has been referred to as an upgrade of the NFDRS map that was designed to represent the greater fuel loads in the western US, there is no mention of this in the Hardy et al. 1998 documentation. The fuel loadings by vegetation cover type are presented for live shrubs, live herbaceous fuels, 1-, 10-, 100-, 1000-, 10,000 + hour downed woody fuels, litter, and duff. All woody fuels are designated as sound. Canopy fuels are not included in Hardy98.

Source:

- As used here originally created for the BlueSky Modeling Framework v1.

References:

- Hardy, C., Menakis, J. P., Long, D. G., Garner, J. L., 1998: FMI/WESTAR emissions inventory and spatial data for the Western United States. Missoula, Montana. USDA Forest Service, RMRS FSL.
- Menakis, J.P. Forester, Missoula Fire Lab, Missoula MT

C.2.3 FCCS v1: Fuel Characteristic Classification System (FCCS) Original Fuel Loading 1-km Map

The FCCS v1 fuel loading map provides fuel loading information at a 1-km scale for the continental United States (McKenzie et al. 2007). The FCCS v1 fuel mapping was completed by assigning one of 112 fuelbeds to each 1 km grid using a rule based assignment methodology described in McKenzie et al. (2007). In this process, standard FCCS v1 fuelbeds and every unique 1 km grid within CONUS were independently assigned a value for Bailey's ecosystem sections (Bailey 1996) and Kuchler's potential natural vegetation classification (Kuchler 1964). (The Bailey's ecosystem sections are a vegetation cover type derived from AVHRR data by

Schmidt et al. 2002.) . These classification values were then used to match fuelbed values with map values. The FCCS fuelbed concept is the most comprehensive of the fuel maps and includes downed woody fuels (1, 10 100, 1000, 10000+ hour), shrubs, herbs, grasses, canopy fuels, dead standing trees (snags), stumps, litter, moss, lichens, and duff. Note: FCCS v1 is no longer supported; the modern version is FCCS-LF (see C.2.5 below).

Source:

- Map downloaded from Fera website 4/23/2010 (however, this file is no longer available on the link shown) http://www.fs.fed.us/pnw/fera/fccs/maps.shtml.

References:

- Bailey, R.G. Ecosystem geography. Springer-Verlag, Inc., New York.
- Kuchler, A.W. 1964. Potential natural vegetation of the coterminous United States. American Geographical Society (with separate map at 1 : 3 168 00). New York. Special Publication 36.
- McKenzie, D., C.L. Raymond, L.-K.B. Kellogg, R.A. Norheim, A.G. Andreu, A.C. Bayard, K.E. Kopper, and E. Elman. 2007. Mapping fuels at multiple scales: landscape application of the Fuel Characteristic Classification System. *Canadian Journal of Forest Research* 37:2421-2437
- Schmidt, KM, Menakis JP, Hardy CC, Hann WJ, Bunnell, DL (2002) Development of coarse-scale spatial data for wildland fi re and fuel management. USDA Forest Service Rocky Mountain Research Station, Fort Collins, General Technical Report RMRS-GTR-87

C.2.4 LANDFIRE: Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) Fuel Loading Models

The LANDFIRE fuel loading model (FLM) map product provides fuel loading values for surface fuels on a 30 m resolution across the CONUS (Lutes et al., 2009, Sikkink et al. 2009). The FLMs were produced from 4046 field plots. Shrubs, herbs, downed woody fuel, litter and duff were quantified at each plot. To produce the FLM map, FLMs were assigned to individual pixels using an imputation approach, filling in the missing data, with LANDFIRE data in the surrounding grids.

Fuel loading values represented in the LANDFIRE fuel loadings map include duff, litter, and 1-, 10-, 100-, and 1000-hour downed woody, shrubs, and herbaceous fuels. Canopy biomass or canopy fuel loadings are not explicitly provided, however it can be computed using associated LANDFIRE map products.

Source:

- LANDFIRE website http://landfire.cr.usgs.gov/viewer/. Downloaded 10/5/2010.

References:

- Lutes DC, Keane RE, Caratti JF (2009) A surface fuels classification for estimating fi re effects. Internat J Wild Fire 18:802-814

- Sikkink P, Keane RE, Lutes DC (2009) Field guide for identifying fuel loading models. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, General Technical Report RMRS-GTR-225

C.2.5 FCCS-LF: Fuel Characteristic Classification System - LANDFIRE Crosswalk Fuel Loading 1-km and 30-m Maps

30-m Map: The FCCS-LF 30 m map is a crosswalk between the standard FCCS fuelbeds (see C.2.3 above) and the LANDFIRE Existing Vegetation Types (EVT) map layer (personal communication, D. McKenzie). **Differences between the original FCCS V1 and FCCS-LF:** The EVT vegetation description used to develop FCCS-LF is more precise than the vegetation types derived using the AVHRR imagery and the Kuchler classes to develop FCCS V1 (personal communication, D. McKenzie). Therefore if the EVT layer is accurately assigned to the corresponding FCCS fuelbed, the resulting fuel loading estimates should more accurately represent what is on the ground.

1-km Map: FCCS-LF at 1 km provides a scaled version of the fuelbed information displayed at 30 m in the LANDFIRE system. FCCS-LF at 1 km was derived for CONUS using the FCCS-LF at 30 m fuel loading map (personal communication, D. McKenzie). An iterative, hierarchal process to identify the most representative fuelbed within the 30 m pixels that correspond to the area covered by each 1 km pixel was used to scale the 30 m scaled fuels information to 1 km. A 5-level hierarchy of increasing generality from specific fuelbeds, to species, to covertype, to specific life forms (conifer, deciduous), to generic category life forms such as “tree”, “shrub”, “nonwoody”, and barren was used and each FCCS fuelbed was associated with a category at each level of the hierarchy. Representative fuelbeds for each 1 km pixel were identified using the most prevalent fuelbed in that 1 km pixel: for example at level one if one fuelbed was associated with more than 50% of the 30 meter pixels, the 1 km pixel was assigned that fuelbed. If a greater than 50% fuelbed match was not found then the process moved on to the second level of species and association was made to a fuelbed. For example, if the dominant species was identified as Ponderosa Pine then the most common fuelbed whose dominant species was Ponderosa Pine was determined to be representative and that fuelbed was associated to the 1 km pixel. If less than 50% was associated to Ponderosa pine the process moved on to the next level of covertype such as pine. The iterative, process was followed until a representative fuelbed was imputed into each 1 km pixel.

Notes:

- Recent efforts have expanded the FCCS-LF maps to include non-CONUS regions (specifically Alaska).

Source:

- http://www.fs.fed.us/pnw/fera/fccs/maps.shtml
  Downloaded FCCS-LF 30 m 4/22/2010
  Downloaded FCCS-LF 1 km 8/17/2012

FCCS-LF 30 m can also be downloaded here

- LANDFIRE website http://landfire.cr.usgs.gov/viewer/

References:

- McKenzie, D., C.L. Raymond, L.-K.B. Kellogg, R.A. Norheim, A.G. Andreu, A.C. Bayard, K.E. Kopper, and E. Elman. 2007. Mapping fuels at multiple scales: landscape application of the Fuel Characteristic Classification System. *Canadian Journal of Forest Research* 37:2421-2437.
- Personal Communication Don McKenzie of U.S. Forest Service Fire and Environmental Research Applications (FERA) Team

C.2.6 Okanogan-Wenatchee National Forest FCCS Custom Fuelbeds 25-m Map

The Okanogan-Wenatche National Forest fuelbed map consists of a set of 83 custom fuelbeds mapped at a 25 m grid resolution across the Okanogan-Wenatchee National Forest. The map was created by linking custom FCCS fuelbeds to a set of forest service vegetation layers (McKenzie et al. 2007). Initially 187 distinct custom fuelbeds were designed by forest managers from the Okanogan-Wenatchee National Forest using the FCCS Standard fuelbed system as a base starting point. The custom fuelbeds were designed to represent species composition, stand structure, stand age, and disturbance history across the vegetation and fuel types present on the forest (McKenzie et al. 2007). A similar rules-based approached, as described for FCCS V1, was to used map the landscape for each 25 m pixel (McKenzie et al. 2007). The LANDSAT Thematic Mapper cover classification cover layer and a polygon layer (WenVeg), developed by the Okanogan-Wenatchee National Forest using aerial photos and site visits were used to assign FCCS fuelbeds (in McKenzie et al. 2007). A critical criterion for fuelbed assignment was that each fuelbed-map pixel match had to be consistent with the WenVeg polygon layer because local managers were confident that the WenVeg layer accurately represented on the ground vegetation.

Source:

- http://www.fs.fed.us/pnw/fera/fccs/maps.shtml
  Downloaded 4/23/2010

References:

- McKenzie, D., C.L. Raymond, L.-K.B. Kellogg, R.A. Norheim, A.G. Andreu, A.C. Bayard, K.E. Kopper, and E. Elman. 2007. Mapping fuels at multiple scales: landscape application of the Fuel Characteristic Classification System. *Canadian Journal of Forest Research* 37:2421-2437.

C.2.7 CVS: Pacific Northwest Current Vegetation Survey

For the Tripod Fire, observed fuel information was obtained through communications with the Okanogan-Wenatchee National Forest (Elizabeth Peterson). The Okanogan-Wenatchee Forest provided a set of field data sampled in the late 1990s by the CVS (Johnson 2001). These data were sampled following the protocol outlined in Johnson 2001, who describes the standard tree and fuels inventory techniques used by the CSV inventory team. The CSV team used fixed circular plots to collect tree species, size, structure, and health data. A modified version of

Brown's fuel inventory procedures was used to collect data for downed woody fuel and forest floor biomass a (Brown 1974; Johnson 2001).

The woody fuels data were processed for each plot located within the Tripod Fire and summarized into size classes (10-hr, 100-hr, 1000-hr and total woody fuels). In addition the biomass available to burn was calculated following Brown 1974. The resulting dataset was used as an observation-based dataset to compare fuel loading maps used in the Tripod Fire test case.

Source:

- Okanogan-Wenatchee National Forest (Personal communication with Elizabeth Peterson, Area Vegetation Inventory Coordinator). Data received: 8/11/2010.
- Additional data available here http://www.fs.fed.us/r6/survey/

References:

- Johnson 2001. Field Procedures for the Current Vegetation Survey, V. 2.04, USDA Forest Service, Pacific Northwest Region, Portland, OR, 97208, 151 pp. Available for download at http://www.fs.fed.us/r6/survey/document.htm
- Brown, James K. 1974. Handbook for inventorying downed woody material. Gen Tech, Rep. INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p.

C.3 CONSUMPTION

C.3.1 Consume

Consume v3 and v4 (Prichard et al., 2006) predicts fuel consumption by strata for each of the following fuels/vegetation: canopy, shrubs, herbaceous, downed woody fuels (1-, 10-, 100-, 1000-, 10,000+ hour fuels), litter, moss, lichen, and duff. Version 4.0 is similar to v3.0 but is rewritten in Python. Both versions were used here. Consume calculates consumption for duff, litter, and woody fuels using empirically derived algorithms. Default (i.e., rules of thumb) equations are used to predict canopy, shrub and herbaceous fuel consumption. Consume partitions fuel consumption into flaming and smoldering consumption using set proportions for each fuels strata (Prichard et al. 2006).

Notes:

- Consume also can compute emissions for pile burns but these were not used here.
- Several versions of Consume were used in SEMIP (specifically v3.0 as incorporated into the BlueSky Framework and v4.0 independently). For the 2008 NEI, the 2006 Tripod Complex, and the 2007 Bugaboo Complex, Consume was run using a Python-based application produced by Michigan Tech. For some runs, the Consume module within the BlueSky framework was used.
- Consume has been undergoing significant development work in recent years, including conversion to a Python-based code and fixes to the underlying code based in part on findings developed for SEMIP. Consume should be retested after this development effort finishes.

Source:

- http://www.fs.fed.us/pnw/fera/research/smoke/consume/consume_download.shtml.

References:

- Prichard, S.J., Ottmar, R.D., and G.K. Anderson. 2006. Consume 3.9 User's Guide. Available for download at: http://www.fs.fed.us/pnw/fera/research/smoke/consume/consume30_users_guide.pdf

Inputs:

- Fuel Loading (Section 4.1)
- Fuel Category (Natural. Piles, Activity)
- Ecoregion (determines which set of regionally developed fuel consumption algorithms to use)
- 1000-hr Fuel Moisture
- Duff Fuel Moisture
- Percent of Canopy Biomass Consumed
- Percent Area Blackened

C.3.2 FOFEM: First Order Fire Effects Model

FOFEM v5.7 provides estimates of fuel consumption for several fuel layers. Consumption of the canopy, shrubs, herbaceous fuels, downed woody fuels (1-, 10-, 100-, 1000+ hour fuels), duff, and litter are accounted for within the model. To predict consumption of the woody fuels, FOFEM uses the Burnup model (Albini and Reinhardt 1995, Albini and Reinhardt 1997). Burnup is a combustion physics model that estimates woody fuel combustion (FOFEM 5.7 Program Users Guide). Litter and duff consumption can also be estimated using Burnup but in many cases duff consumption is predicted using empirically derived equations (Reinhardt et al. 1997; Reinhardt and Dickenson 2010). Shrub, herbaceous and canopy fuel consumption are predicted using general rule-of-thumb algorithms. The flaming and smoldering phases of combustion are discerned internally within the model by a process that uses Burnup to calculate heat intensity. The threshold for sustaining flaming consumption is set at $\geq$15 kW/m^2. At heat intensities less than 15 kW/m^2 all consumption is assumed to be smoldering (FOFEM 5,7 Program Users Guide).

Source:

- Acquired via http://www.firelab.org/science-applications/fire-fuel/111-fofem on 8/1/2010.

References:

- Albini, F.A. and E.D. Reinhardt. 1995. Modeling ignition and burning rate of large woody natural fuels. Int. J. Wildland Fire. 5(2): 81-91.
- Albini, F.A. and E.D. Reinhardt. 1997. Improved calibration of a large fuel burnout model. Int. J. Wildland Fire. 7(2):21-28.

- Reinhardt, E., Keane, R.E., Brown, J.K., 1997. First order fire effects model: FOFEM 4.0 user's guide. General Technical Report INT-GTR-344, USDA Forest Service.
- Reinhardt, Elizabeth D.; Dickinson, Matthew B. 2010. First-order fire effects models for land Management: Overview and issues. Fire Ecology. 6(1): 131-142.

Inputs:

- Fuel Loading (Section 4.1)
- Ecoregion (determines which set of regionally developed fuel consumption algorithms to use)
- Season
- 10-hr Fuel Moisture
- 1000-hr Fuel Moisture
- Duff Fuel Moisture
- Percent of Canopy Biomass Consumed
- Fuel Category (Natural, Piles, Slash)

C.3.3 MTBS: Monitoring Trends in Burn Severity

The MTBS burn severity maps include gridded estimates of burn severity categorized by unburned, low, moderate, high severity (Eidenshink et al., 2007). When coupled with composite burn inventories (Key and Benson 2006) or field sampled fuel consumption data, MTBS burn severity maps can be used to provide a remotely sensed estimate of fuel consumption across landscapes (Justice et al. 2010). Following the procedures in Key and Benson 2006 the fraction of fuel consumed is visually estimated in the field for each fuel strata across an area of interest (Key and Benson 2006). For the Tripod Fire, Justice et al. (2010) coupled composite burn inventory methodology with post-fire field sampling of vegetation and fuels data to produce indices relating fuel consumption to MTBS burn severity. In our study, we utilized the same fuel consumption indices and the mapped MTBS burn severity classes for the Tripod Fire to produce a composite map of observed fuel consumption estimates across the Tripod Fire area.

Source:

- Monitoring Trends in Burn Severity (MTBS) Project acquired via *www.mtbs.gov on 9/30/2010*

References:

- Eidenshink J., Schwind B., Brewer K., Zhu Z.-L., Quayle B., and Howard S. (2007) A project for monitoring trends in burn severity. Fire Ecology Special Issue, 3, 1, 3-21.
- Key, C.H., Benson, N.C., 2006. Landscape Assessment: Ground measure of severity, the Composite Burn Index; and Remote sensing of severity, the Normalized Burn Ratio. In: Lutes, D.C., Keane, R.E., Caratti, J.F., Key, C.H., Benson, N.C., Sutherland, S., Gangi, L.J. FIREMON: Fire Effects Monitoring and Inventory System. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT. Gen. Tech. Rep. RMRS-GTR-164-CD: LA 1–51..
- Justice, E, Cheung, B., Danse, W., Myrick, K., Willis, M., Prichard, S., and J.W. Skiles. 2010. Effect of fuel treatments on carbon flux during a wildfire using satellite imagery:

Okanogan-Wenatchee National Forest. Proceedings of the ASPRS 2010 Annual Conference. San Diego, California. April 26-30, 2010.

Inputs:

- MTBS burn severity map

C.3.4 FEPS: Fire Emissions Production Simulator (FEPS) Consumption

The FEPS model, developed by the USFS Fire and Environmental Research Applications (FERA) team assigns hourly consumption from total consumption based on a series of equations (see Anderson et al., 2004). FEPS allows for fire area growth over time using two methods, linear progression or a freely spreading oval. For prescribed burns, the linear progression method is used.

Source:

- Used as incorporated into the BlueSky Smoke Modeling Framework v3.1 (FEPS module version 2)

References:

- *Fire Emission Production Simulator (FEPS)*, version 1.1; Fire and Environmental Research Applications Team: Seattle, WA, USA, 2005.
- Anderson, G. K., Sandberg, D. V., and Norheim, R. 2004. Fire emission production simulator User's Guide, version 1.0. Produced for the Joint Fire Science Program (98-1-9-05).
- FEPS User's Guide: http://www.fs.fed.us/pnw/fera/feps/FEPS_users_guide.pdf

C.3.5 EPM: Emission Production Model

EPM, developed by the USFS Fire and Environmental Research Applications team, is a source strength model that combined what was known about factors that control biomass consumption and combustion efficiency to estimate emission rates of particulate matter and other trace gases (Sandberg and Peterson, 1984).

Source:

- Used as incorporated into the BlueSky Smoke Modeling Framework v3.1 (EPM module version 1)

References:

- Sandberg, D.V. and Peterson, J. (1984) A Source Strength Model for Prescribed Fire in Coniferous Logging Slash. Annual Meeting Air Pollution Control Association, Pacific Northwest Section, November 12-14, 1984, Portland, Oregon.

C.4 TIME RATE OF CONSUMPTION

C.4.1 WRAP Time Profile: Western Regional Air Partnership (WRAP) Wildfire Time Profile

The WRAP time profile is a static lookup table that allocates daily emissions to hourly emissions. It is based on expert judgment. The hourly allocation is shown in the table below.

Table C1: WRAP Time Profile

Hour (Local Time)	Percentage of Emissions
1	0.57
2	0.57
3	0.57
4	0.57
5	0.57
6	0.57
7	0.57
8	0.57
9	0.57
10	2
11	4
12	7
13	10
14	13
15	16
16	17
17	12
18	7
19	4
20	0.57
21	0.57
22	0.57
23	0.57
24	0.57

Source:

- Used as incorporated into the BlueSky Smoke Modeling Framework v3 (BSF WRAP Time Profile module version 1)

References:

- Air Sciences, Inc. *Integrated Assessment Update and 2018 Emissions Inventory for Prescribed Fire, Wildfire, and Agricultural Burning*; Air Sciences, Inc.: Denver, CO, USA, 2005. http://www.wrapair.org/forums/fejf/documents/emissions/WGA2018report20051123.pdf

C.4.2 FEPS: Fire Emissions Production Simulator (FEPS) Prescribed Fire Time Profile Curve

Within the FEPS model (see also C.3.4 above) the time profile of a prescribed fire is described with two curves, one for the flaming phase of the fire and one for the smoldering phase. The flaming phase of combustion is modeled as directly proportional to area burned for a given hour. The smoldering combustion is modeled to continue after fire growth with exponential decay.

Source:

- Used as incorporated into the BlueSky Smoke Modeling Framework v3 (FEPS module version 2)

References:

- *See references in C.3.4.*

Inputs:

- Fuel consumption
- Meteorological information: daily maximum and minimum temperature, daily maximum and minimum relative humidity, transport wind speed, time of sunset, mid-day time, and pre-dawn time
- Fire size

C.5 EMISSIONS

C.5.1 FEPS: Fire Emissions Production Simulator (FEPS) Emissions

The FEPS model (see also C.3.4 above) simulates total combustion, time rate of combustion and ultimately computes speciated emissions. Emission of CO_2, CO, CH_4, and $PM_{2.5}$ in the form of mass (tons) emitted per fire are based on emission factors derived through empirical relationships used within the model. Through a linear relationship, derived from field observations, the emission factors are calculated from combustion efficiency. The combustion efficiency corresponds to the fire phase, smoldering or flaming, under which the emissions were released. The combustion efficiency is calculated through the consumption portion of FEPS and is assumed to reflect the fuel type and moisture. The fuel information is only related to the emission factors algorithm through combustion efficiency. Emissions themselves are computed by multiplying the calculated emission factors (mass of emissions per mass of fuel consumed) by the quantity of fuels consumed simulated in the model.

Source:

- Used as incorporated into the BlueSky Smoke Modeling Framework v3.1 (FEPS module version 2)

References:

- *See references in C.3.4.*

Inputs:

- Combustion efficiency (derived from FEPS Consumption C.3.4)
- Mass of fuel consumed (tons) (derived from FEPS Consumption C.3.4)

C.5.2 FOFEM Emissions

Emissions from FOFEM were produced using the default emission factors (Ward et al., 1993; Hao, 2003 unpublished) and default combustion efficiencies of 0.97 (flaming) and 0.67 (smoldering). The emission factors are static and are provided for reference in Table C2. Proportions of fuel consumed during flaming and smoldering are determined using heat intensities calculated by Burnup, the woody fuel consumption model within FOFEM, and depends on heat intensity. Sustained flaming consumption is assumed at heat intensities greater than 15 kW/m^2. At lower heat intensities, all consumption is assumed to be in the smoldering phase (FOFEM 5.7 Help document).

Table C2. FOFEM v5.7 Emission Factors by Pollutant (lb/ton)

Combustion Phase	$PM_{2.5}$	PM_{10}	*CO*	CO_2	CH_4	SO_2	*NOx*
Flaming	5	6	13	3556	2	2	6
Smoldering	45	53	603	2456	28	2	0

Source:

- Acquired via http://www.firelab.org/science-applications/fire-fuel/111-fofem on 8/1/2010.

References:

- Ward DE, Peterson J, Hao WM (1993) An inventory of particulate matter and air toxic emissions from prescribed fires in the USA for 1989. In 'Proceedings of the Air and Waste Management Association 1993 annual meeting and exhibition, Denver, CO'. pp. 1–19.
- Reinhardt, E., Keane, R.E., Brown, J.K., 1997. First order fire effects model: FOFEM 4.0 user's guide. General Technical Report INT-GTR-344, USDA Forest Service.
- Hao, WM 2003, unpublished report; On file at the Missoula Fire Lab, Missoula MT. Reinhardt, Elizabeth D.; Dickinson, Matthew B. 2010. First-order fire effects models for land Management: Overview and issues. Fire Ecology. 6(1): 131-142.

Inputs:

- Fuel Loading (Section 4.1)
- Ecoregion
- Season
- 10-hr Fuel Moisture
- 1000-hr Fuel Moisture

- Duff Fuel Moisture
- Percent of Canopy Biomass Consumed
- Fuel Category (Natural, Piles, Slash)

C.5.3 Consume Emissions

Emissions from Consume v3 were estimated using the default static emission factors, which are an average of all Consume emission factors (Pritchard et al. 2006). These emission factors are provided in Table C3. The emissions are computed by multiplying these factors by the proportion of fuel consumed in the flaming and smoldering phases, which varies depending on fuel type. This is calculated in the consumption portion of the Consume v3 model.

Table C3. Consume Emission Factors by Pollutant (lb/ton)

Combustion Phase	*$PM_{2.5}$*	*PM_{10}*	*PM*	*CO*	*CO_2*	*CH_4*	*NMCH*
Flaming	13	15	23	90	2522	3	5
Smoldering	19	24	34	209	2285	11	10

Source:

Acquired via http://www.fs.fed.us/pnw/fera/research/smoke/consume/consume_download.shtml

References:

- Prichard, S.J., Ottmar, R.D., and G.K. Anderson. 2006. Consume 3.0 User's Guide. Available for download at: http://www.fs.fed.us/pnw/fera/research/smoke/consume/consume30_users_guide.pdf

Inputs:

- Fuel Consumption by phase

C.5.4 FINN Emissions Factors

FINN uses a suite of emissions factors compiled from the most recently available research, including Akagi et al. (2011), McMeeking (2008), and factors updated from Andreae and Merlet (2001). FINN emissions were calculated via the BlueSky Smoke Modeling Framework.

Source:

- Used as incorporated in the BlueSky Smoke Modeling Framework (FINN Emissions module version 1)

References:

- Wiedinmyer, C., Akagi, S. K., Yokelson, R. J., Emmons, L. K., Al-Saadi, J. A., Orlando, J. J., Soja, A. J. The Fire INventory from NCAR (FINN): a high resolution global model to estimate the emissions from open burning, Geosci. Model Dev. Discuss. 2011, 3, 2439-2476.
- Akagi, S. K., Yokelson, R. J., Wiedinmyer, C., Alvarado, M. J., Reid, J. S., Karl, T., Crounse, J. D., and Wennberg, P. O.: Emission factors for open and domestic biomass burning for use in atmospheric models, Atmos. Chem. Phys., 11, 4039–4072, doi:10.5194/acp-11-4039-2011, 2011.
- Andreae, M. O. and Merlet, P.: Emission of trace gases and aerosols from biomass burning, Global Biogeochem. Cy., 15(4), 955–966,2001.
- McMeeking, G. R.: The optical, chemical, and physical properties of aerosols and gases emitted by the laboratory combustion of wildland fuels, Ph.D. Dissertation, Department of Atmospheric Sciences, Colorado State University, 109–113, Fall 2008.

Inputs:

- Land Cover Type (MODIS classification)
- Mass of fuel consumed (kg)

C.5.5 FLAMBE Emissions Factors

FLAMBE only calculates emissions for $PM_{2.5}$. The emission factor FLAMBE uses is the product of a carbon fraction and an aerosol emissions factor. Both of these terms are dependent on land cover type. FLAMBE does not distinguish between flaming and smoldering, and all emissions are assigned to the flaming phase in the BlueSky Smoke Modeling Framework.

Source:

- Used as incorporated in the BlueSky Smoke Modeling Framework (FLAMBE Emissions module version 1)

References:

- Reid J., Hyer E., Prins E., Westphal D., Zhang J., Wang J., Christopher S., Curtis C., Schmidt C., Eleuterio D., Richardson K., Hoffman J. (2009). Global monitoring and forecasting of biomass-burning smoke: description of and lessons learned from the Fire Locating and Modeling of Burning Emissions (FLAMBE) program. *IEEE J. of Selected Topics in Appl. Earth Obs. And Rem. Sens.* Vol 2., No.3

Inputs:

- Land cover type (FLAMBE specific)
- Mass of fuel consumed (kg)

C.5 PLUME RISE

C.5.1 FEPS: Fire Emissions Production Simulator (FEPS) Plume Rise

FEPS calculates three plume rise quantities. It uses a modified version of the classical empirical plume rise equations developed by Briggs to calculate a maximum plume rise. FEPS also provides a second empirical approach for calculating both maximum and minimum plume rise. All FEPS plume rise calculations are hourly and depend on hourly consumption. Not all emissions in FEPS are subject to plume rise; a fraction of the emissions are assigned no plume rise based on calculated entrainment efficiency. The default BlueSky implementation, used for this case, of FEPS uses the modified Briggs method to calculated plume top height and the FEPS empirical approach for plume bottom.

Source:

- Used as incorporated into the BlueSky Smoke Modeling Framework (FEPS module version 2)

References:

- *See references in C.3.4*
- Briggs, G.A. Plume Rise Equations. In *Lectures on Air Pollution and Environmental Impact Analysis*; Haugen, D.A., Ed.; AMS: Boston, MA, USA, 1975; pp. 59–111.

C.5.2 MISR: Multi-angle Imaging Spectroradiometer (MISR) Plume Height Project

Smoke plume top heights can be derived from the MISR instrument, onboard NASA's Terra satellite, using stereoscopic analysis as MISR's multiple cameras view the same location from different viewing angles. The MISR Plume Height Project provides a database of analyzed smoke plumes. Project summary files contain information on a plume-by-plume basis, including several measures of plume top height, including median and maximum plume top heights with and without corrections for wind.

Source:

- Obtained via http://misr.jpl.nasa.gov/getData/accessData/MisrMinxPlumes/ on 4/4/2008
- Example summary data file link: http://eosweb.larc.nasa.gov/MISR/plume/NorthAmerica/NorthAmerica2005/NorthAmerica2005_PlumeDatabase.txt
- Field used: 21 – Median wind-corrected height

References:

- Kahn, R.A.; Li, W.-H.; Moroney, C.; Diner, D.J.; Martonchik, J.V.; Fishbein, E. Aerosol source plume physical characteristics from space-based multiangle imaging. *J. Geophys. Res.* **2007**, *112*, D11205:1–D11205:20.
- Nelson, D.L.; Chen, Y.; Kahn, R.A.; Diner, D.J.; Mazzoni, D. Example applications of the MISR INteractive eXplorer (MINX) software tool to wildfire smoke plume analyses. *Proc. SPIE* **2008**, *7089*, doi:10.1117/12.795087.

- Product description page: http://misr.jpl.nasa.gov/getData/accessData/MisrMinxPlumes/productDescription/

C.5.2 CALIPSO: Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) aerosol vertical profiles

The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument onboard NASA's CALIPSO satellite uses active lidar to measure aerosol vertical profiles. The profile information CALIPSO provides is of high vertical resolution (up to 30 m) but the CALIPSO instrument has a very narrow swath that sees only a small fraction of smoke plumes. With knowledge of CALIPSO overflight times, smoke plumes can be matched and found in CALIPSO data. The data product used here is the Lidar Level 2 Vertical Feature Mask Data Product (DP 2.1D). This product provides a vertical map of aerosol types along the satellite orbit track. Aerosol types are determined through an automated algorithm. Although the product provides a "smoke aerosol" type, all aerosol types were used as the automated typing algorithm classified many known smoke plumes as other aerosol types.

Source:

- Data product used: CAL_LID_L2_VFM-Prov-V2-01
- Obtained via http://eosweb.larc.nasa.gov/HBDOCS/langley_web_tool.html on 5/1/2008

References:

- Winker, D.M.; Hunt, W.H.; McGill, M.J. Initial performance assessment of CALIOP. Geophys. Res. Lett. 2007, 34, L19803:1–L19803:5.
- CALIPSO Quality Statements; National Oceanic and Atmospheric Administration: Washington, DC, USA. Available online: http://eosweb.larc.nasa.gov/PRODOCS/calipso/Quality_Summaries (accessed on 15 December 2011).
- Winker, D.M.; Vaughan, M.A.; Omar, A.; Hu, Y.; Powell, K.A.; Liu, Z.; Hunt, W.H.; Young, S.A. Overview of the CALIPSO mission and CALIOP data processing algorithms. J. Atmos. Ocean. Technol. 2009, 26, 2310–2323.

C.6 DISPERSION

C.6.1 HYSPLIT: Hybrid Single Particle Lagrangian Integrated Trajectory model

The HYSPLIT model is used for computing both simple trajectories of plume transport and complex dispersion of plume spread. The model allows for a choice between the puff or particle approaches. Advection (transport) and diffusion (spread) calculations are made in a Lagrangian framework, while concentrations are calculated on a fixed Eulerian grid. The HYSPLIT model is designed to simulate plume dispersion and transport over uneven terrain, for long-range plume footprints, and in a changing wind regime. It is used around the world to simulate smoke plume surface concentrations and plume footprints.

HYSPLIT can operate in three different modes known as: particle-particle, particle-puff, or puff-puff. Each mode represents how the model defines the way the plume is released, as a puff or a cloud of particles. The puffs and/or particles are released every time step, forming a plume that shifts with the wind and turbulence. Particle-particle represents particle clouds in the vertical and in the horizontal, particle-puff represents particle cloud in the vertical and puff in the horizontal, and puff-puff represents puff in the vertical and horizontal. Each puff or particle represents the mass emitted by the fire. The mass distribution within the puff is assumed normal (Gaussian) while the mass distribution within the particle cloud is calculated after the winds has moved the particles. The choice of mass represented by each particle must be carefully selected so that enough particles are emitted to represent the plume motion without releasing so many particles that the simulation becomes computationally slow. The mode choice will influence the surface concentration result. It is important to note that HYSPLIT does not include complex chemical transformation algorithms within the model and modeling of ozone production should be done with a chemical transport model, such as CMAQ (described in C6.2).

Source:

- Used as incorporated into the BlueSky Smoke Modeling Framework v3.3 (HYSPLIT module version 5)

References:

- Draxler, R.R.; Hess, G.D. 1998. An overview of the Hysplit_4 modeling system for trajectories, dispersion, and deposition. Aust. Met. Mag., 47, 295-308.

- Draxler, R.R.; Hess, G.D. 1997. Description of the Hysplit_4 modeling system. NOAA Technical Memorandum ERL ARL-224, December, revised January 2004.

- General HYSPLIT Information link: http://www.arl.noaa.gov/hysplit.php

- User's Guide: http://www.arl.noaa.gov/documents/reports/hysplit_user_guide.pdf

Inputs:

- Three-dimensional, hourly gridded modeled meteorological data
- Fire information (size, location)
- Vertical distribution of emissions
- Emissions rate of smoke plume chemical species

C.6.2 CMAQ: Community Multi-scale Air Quality modeling system

The CMAQ system is a one-atmosphere chemical transport model designed to compute air quality chemistry (i.e., ozone production), deposition, visibility reduction, and gas and particulate concentrations. All modeled chemistry, deposition, etc. are done within the individual grid cells with a mass-balance approach between neighbors to account for transport due to wind (CMAQ is an Eulerian grid model). CMAQ allows for the modeling of within-plume chemistry and smoke-plume regional-airshed interactions and ozone production due to fire emissions can be examined using CMAQ. Because CMAQ is a holistic model, emissions from sources other than fire are required. Emission from biogenic (emissions from vegetation), urban, vehicle, and other anthropogenic sources are needed to appropriately model air quality and smoke plume impacts. All emissions are translated into CMAQ ready format through the SMOKE pre-processing system.

The simulation of the atmospheric chemical processes within every grid cell at every time step is computationally demanding. Often the computational time will limit the modeling grid resolution and/or domain size, in particular when operating in operational forecast mode.

Source:

- Version 4.51 March 17, 2006 release used as incorporated in the BlueSky Gateway forecast system

References:

- Byun, D. W. and Schere, K. L.: Review of the governing equations, computational algorithms, and other components of the Models-3 Community Multiscale Air Quality (CMAQ) Modeling System, Appl. Mech. Rev., 59, 51–77, 2006.
- Houyoux, M.R., J. Vukovich, and J. Brandmeyer, 2000: Sparse Matrix Operator Kernel Emissions Modeling System (SMOKE) user manual. MCNC-North Carolina Supercomputing Center, Environmental Programs, Research Triangle Park, NC.
- Houyoux, M.R. and Z. Adelman, 2001: Quality assurance enhancements to the SMOKE Modeling System. U.S. Environmental Protection Agency's International Emission Inventory Conference: One Atmosphere, One Inventory, Many Challenges, Denver, CO, May 1-3.
- EPA webpage description: http://www.epa.gov/AMD/CMAQ/cmaq_model.html
- CMAQ community working group and webpage http://www.cmascenter.org/

Input:

- Three-dimensional, hourly gridded modeled meteorological data
- Fire information (size, location)
- Plume rise information: height the emissions should be placed
- Emissions rate of smoke plume chemical species

C.7 MODELING FRAMEWORKS

C.7.1 BlueSky Modeling Framework

The BlueSky Modeling Framework is a modular modeling framework that links models and datasets of fuels, consumption, time profile, emissions, plume rise, and dispersion (Larkin et al. 2009). BlueSky takes as inputs fire information and meteorological data as well as information on fuel moistures. BlueSky wraps existing models and datasets such as the Consume model and the NFDRS fuel loading map allowing them to be linked into modeling pathways easily. Where possible the original models were used directly. For larger modeling applications BlueSky was used to enable the processing to be done more easily. Additionally, data from the BlueSky Gateway real-time forecasting system was used for long-term comparisons of smoke concentrations and plume rise in order to determine how well real-time systems work for these applications.

Source:

- Available by contacting Sim Larkin of the U.S. Forest Service
- BlueSky Modeling Framework v3 used here except as noted.

References:

- Larkin, N.K., S.M. O'Neill, R. Solomon, C. Krull, S. Raffuse, M. Rorig, J. Peterson, and S.A. Ferguson (2009), "The BlueSky smoke modeling framework." *International Journal of Wildland Fire,* 18, 906-920

C.7.2 SmartFire 2 Framework

SmartFire 2 is a geospatial software framework that ingests, associates, and reconciles multiple electronic datasets containing fire occurrence information. Inputs to SmartFire 2 can include fire occurrence reports (such as ICS-209 reports or state prescribed burn databases), burn scar polygons, satellite-based fire detections, and other sources of fire occurrence information. SmartFire 2 uses spatio-temporal overlap, along with uncertainty values, to associate fires information from multiple data sources. SmartFire then employs user-specified algorithms to reconcile double-counted fires into a single output stream of merged fire information. For SEMIP, SmartFire 2 was used primarily in the NEI test case.

Source:

- Available by contacting Sim Larkin of the U.S. Forest Service
- SmartFire v2 used here except as noted.

References:

- Raffuse S., Larkin, N., Lahm P., Du Y. Development of the wildland fire portion of the 2008 National Emissions Inventory. (in prep.)

APPENDIX D: ANALYSIS DETAILS BY OUTPUT LEVEL

This appendix details the analyses identified and analyses performed by output level:
- Fire information (D.1)
- Fuel loading (D.2)
- Total consumption (D.3)
- Time profile of consumption (D.4)
- Emissions (D.5)
- Plume height (D.6)
- Ground smoke concentrations (D.7)
- Total column smoke (D.8) [deprecated for Phase 1]

For each output level, details are given as to the major issues with this kind of information, the need for stratified analysis procedures (e.g., by fire type or ecoregion), what analyses were identified as being potentially part of SEMIP including potential data types, and what analyses were performed for Phase 1 of SEMIP.

D.1 FIRE INFORMATION

Fire occurrence data is of varying quality. Previous studies have found that ground reports can be significantly inaccurate in location and size, while satellite observations can underrepresent the amount of understory burning. In addition, observations of fire from satellite-based instruments can have difficulty in determining exact fire size, and clouds can block satellite observations. Total fire burned area can be complex because, for example, there can be unburned islands within the fire-perimeter.

Fire information used in fire emissions and smoke impact modeling is generally:
- Fire location (latitude & longitude or other geo-referencing)
- Total fire size
- Fire growth by day
- Type of fire (prescribed, wildfire)

Where possible, fire perimeters can be used for fire location, size, and growth per day. Note that sub-daily growth is generally not available from current fire information systems, although such information would be useful in modeling fire emissions and smoke impacts.

Because fire information is generally *remotely sensed* and/or *reported from observations* (or plans), the issues with fire information datasets/systems are generally ones of:
- Coverage (spatial and temporal)
- Completeness (in time, in space, in types of fire, in sizes of fire)
- Accuracy / quality control of information

Satellite hot-spot detection systems have the further issue of interpretation / fitting of the hot spots into fire area.

Fire information sources are generally geographic in nature (even for satellite systems that have specific timings and paths), with different sets of information available based on the fire's geopolitical location with respect to:

- Country
- Region
- State
- Land ownership (e.g., federal, state, private)
- Land ownership subregion (e.g., USFS)

As well as the:

- Type of fire
- Fire size
- Management action involved

Because of this, analyses must be tailored to the various geopolitical boundaries where reporting systems are available. Fire information systems that utilize more than one reporting/detection system also face the challenge of avoiding double counting information that may be reported in more than one system.

D.1.1 Identified Potential Analyses

Cross-comparison of fire detection systems and observed / reported fire information showing:

- Basic statistics (mean/median, quartiles, peak)
- by Size categorization:
    - Largest fires only
    - Smaller fires only
- by Type categorization:
    - Unplanned ignition
    - Planned ignition
- by Regional categorization:
    - All (e.g., CONUS)
    - Geographic region (e.g., Northwest, Southeast, etc...)
    - Regional Planning Organization region (e.g., WRAP)
    - State

Examples of data that can be used to meet these analysis needs are:

- Ground: ICS 209, Helicopter perimeters, GIS perimeter maps, RX fire plan maps
- Satellite: HMS, MODIS—fire detect, burn scar, GOES, LANDSAT burn scar (RSAC)

D.1.2 Analyses Performed in Phase 1

Test cases used (see Appendix B):

- 2008 National Emissions Inventory (NEI)

- 2006 Tripod Complex (Tripod)
- 2007 Bugaboo Complex (Bugaboo)

Scales examined:

- NEI: national scale, daily information and aggregated information up to 1 year.
- Tripod / Bugaboo: individual fire scale, daily information and aggregate information up to the life of the fire (~ monthly).

Datasets/models used (see Appendix C):

- ICS-209 reports (NEI, Tripod, Bugaboo)
- MODIS active detects (NEI, Tripod, Bugaboo)
- GOES WF-ABBA (NEI)
- NOAA Hazard Mapping System (NEI)
- MODIS burn scar (Tripod, Bugaboo)
- MTBS polygons (NEI)
- NIFC (GeoMAC) fire perimeters (Tripod, Bugaboo)
- SmartFire v1 (NEI, Tripod, Bugaboo)
- SmartFire v2 (NEI)

Modeling pathways examined:

- Individual datasets as above

Variables examined:

Analysis Type	**Test Case**	**Variables Examined**
National annual totals	NEI	Total area burned (acres) Fire pixel (hot spot) density (per area)
Detection Rate	NEI	Overall probability of detection (%) Probability of detection by land cover type (%)
Fire level comparisons	Tripod Bugaboo	Total area burned (acres)

Analysis Summary:

Fire information data sources were assessed by intercomparing total area as computed by each dataset and by assessing probability of detection against a known set of large fires from the MTBS project. Large fire detection rates of several satellite detection systems were compared for different land cover types. For the single fire cases (Tripod and Bugaboo) fire areas were either provided by the dataset directly (e.g., ICS-209), calculated as the area of the provided polygon shape (e.g., NIFC fire perimeters), or calculated as the total area of coverage from gridded satellite detects (e.g., MODIS active detects).

There is substantial variability in total area reported, both for individual large fires and fires aggregated to the national level. Differences at the aggregated national level are driven not only by the discrepancies in area estimation for specific fires, but also by the number of fires reported. The ability for satellite-based active fire detection algorithms to detect known large fires from the MTBS project was examined. MODIS Terra detected 50% and HMS detected 85% of all MTBS fires with a final size of 500–1,000 acres. Forest fires were much more likely to be detected than fires in grass or shrublands. While national authoritative systems provide useful information on wildfires, there is no comprehensive or authoritative information on prescribed burn totals.

See also:

- On detection rates: Raffuse et al. (2012)
- On overall annual fires: Larkin et al. (2012)
- On Tripod case fire size comparisons: Drury et al. (2012)

D.2 FUEL LOADING

Fuel loading data is one of the principal pieces of information needed to estimate fire emissions and smoke impacts. Fuel loadings are typically developed from plot level data. Mapped fuel loadings combine these plots with remote sensing to assign fuels across the landscape. Mapped fuel loadings are available for the U.S. from several sources, and fuel loading plots are both routinely collected (e.g., from the Fuels Inventory Analysis project) and specially developed for specific projects. Photo-series and other tools provide managers a shortcut for doing extensive plot surveys when developing customized fuelbeds for their area. Fuelbed descriptions can vary with respect to the types of fuels included (e.g., whether canopy fuels are included, whether deep organic layers are included) and the exact categories used.

Fuel loading information used in fire emissions and smoke impact modeling is generally:

- Total fuel loading
- Fuel loading by category (e.g., 1-hr fuels, 10-hr fuels, etc…)
- Fuel type (used by some consumption models in lieu of full loadings)

In general, the exact nature of the fuel loading information used in fire emissions and smoke impact modeling is determined by the consumption model used. Some consumption models utilize only simple descriptions of the fuelbed, while others utilize very complex fuelbed descriptions like those produced for the FCCS system.

Because mapped fuel loading information is a combination of both observed plot data and remotely sensed data, the issues with fuel loading information are generally ones of:

- Accuracy / applicability of the fuelbed assigned to a given location
- Completeness of the fuel loading description
- Natural variability in fuel loading across scales from the plot scale to the landscape scale

Fuelbed information and data used in fire emissions and smoke impact modeling are generally based on mapped systems that are available across the country. In some places, local observations / datasets of fuels information may be available. Because of this, analyses can be done both nationally and for specific locations where additional fuel loading information is available.

D.2.1 Identified Potential Analyses

Cross-comparison of fuel showing:

- Basic statistics (ave, min, max, mean, median, sd, quartiles)
- Spatially aggregated
- Categorical statistics to compare fuel types
- by Vegetation type categorization:
  - Ecoregion
  - Shrubs / Grasses / Forest / Forest Type, etc.
- by Fuel Size/Fuelbed Component categorization
  - 1-hr / 10-hr / 100-hr, 1000-hr, 10,000-hr, >10,000-hr downed woody fuel loadings, Canopy fuel loadings (live foliage, dead standing trees), shrub fuel loadings, herbaceous fuel loadings, litter and duff fuel loadings
- by Regional categorization:
  - All (e.g., CONUS)
  - Geographic region (e.g., Northwest, Northeast, Southeast, Southwest)

Examples of data that can be used to meet these analysis needs are:

- Plots: Forest Inventory and Analysis (FIA) + other vegetation plots
- Satellite: LANDSAT, MODIS
- Mapped fuels: FCCS, LANDFIRE, regional

D.2.2 Analyses Performed in Phase 1

Test cases used (see Appendix B):

- Fires Everywhere
- 2008 National Emissions Inventory (NEI)
- 2006 Tripod Complex (Tripod)
- 2007 Bugaboo Complex (Bugaboo)

Scales examined:

- Fires Everywhere: 1-km grid over CONUS
- NEI: 30-m fuels aggregated for large fire areas for all of 2008
- Tripod/Bugaboo: 25-m/30-m and 1-km fuels statistically aggregated to fire area

Datasets/models used (see Appendix C):

- NFDRS 1-km fuel loading map (Fires Everywhere, Tripod)
- Hardy98 1-km fuel loading map (Fires Everywhere, Tripod)
- FCCS v1 1-km fuel loading map (Fires Everywhere, Tripod)
- FCCS-LF 1-km fuel loading map (Tripod, Bugaboo)
- FCCS-LF 30-m fuel loading map (NEI, Tripod, Bugaboo)

- LANDFIRE/FLM 30-m fuel loading map (NEI, Tripod, Bugaboo) Note: LANDFIRE canopy fuel loadings were developed to supplement the FLMs (see Appendix C).
- Okanogan-Wenatchee Custom 25-m FCCS fuel loading map
- FINN 1-km fuel loadings (NEI)
- FLAMBE' 30-arc second fuel loadings (NEI)
- Current Vegetation Survey (CVS) Plot Data

Modeling pathways examined:

- Individual datasets as above
- Fuels were extracted for fire perimeter locations for NEI, Tripod, Bugaboo

Variables examined:

Analysis Type	Test Case	Variables Examined (where available)
National annual totals	NEI	*Totals summed as tons and tons/acre* Total Fuel Loading Total Surface Fuel Loading Total Woody Fuel Loading Total Sound Woody Fuel Loading Total Rotten Woody Fuel Loading Total Canopy Loading
1-km "pixel" locations	Fires Everywhere	*all as tons/acre* Total Downed Woody Fuel Loading Canopy Fuel Loading Shrub Fuel Loading Grass Fuel Loading Duff Fuel Loading 1-hr Fuel Loading 10-hr Fuel Loading 100-hr Fuel Loading 1000-hr Fuel Loading 10000-hr Fuel Loading 10000-hr+ Fuel Loading
Fire level comparisons	Tripod Bugaboo	*Aggregate total over all grid cells in the fire area (in tons):* Total Fuel Loading *Statistics done on fuel strata for all grid cells within the fire area (in tons/acre):* Total Fuel Loading Total Surface Fuel Loading Total Woody Fuel Loading Total Sound Woody Fuel Loading Total Rotten Woody Fuel Loading Canopy Fuel Loading Stump Fuel Loading Shrub Fuel Loading Grass/Forb Fuel loading Litter Fuel Loading Duff Fuel Loading

Variables available by dataset (black indicates availability):

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

Analysis Summary:

Fuels data were analyzed for a number of test cases that span a range of application scales, from a single wildfire complex to a national aggregate (i.e., looking at all large fires in a single year) scale. Both older (e.g., NFDRS, Hardy et al. 1998) and newer (e.g., LANDFIRE-FLMs, FCCS-LF) fuel maps were compared. The fuel datasets themselves provide data from 25-m to 1-km gridded squares across the U.S. Not all fuel strata are available for all datasets. For LANDFIRE ,canopy fuel loadings were generated using LANDFIRE canopy heights and canopy bulk densities.

In the Fires Everywhere test case, fuels were examined for every pixel within the continental United States. Fires Everywhere type analyses are useful for setting baseline conditions on large scales such as a land management unit, a regional analysis, or a national analysis. The results show that large discrepancies not only exist regionally, but that these differences vary considerably from 1-km pixel to 1-km pixel. The NEI test case was used to examine fine-scale fuel maps (30-m national coverage) in order to determine whether pixel-to-pixel comparisons show systemic or merely random differences.

Fuel loadings were summed on all wildfires defined by MTBS as large (greater than 500 acres in the east and 1000 acres in the west). These fires account for the bulk of the 2008 emissions (e.g., Raffuse et al., 2012). The NEI case was also used to evaluate satellite methodologies from FINN and FLAMBE. Differences were found to be large even in aggregate and even between the FCCS-LF and LANDFIRE fuels, which use the same base data to allocate fuelbeds across the landscape (but with different fuelbeds). The two wildfire complex cases—Tripod and Bugaboo—were selected to represent single large wildfire events and allow for more detailed comparisons of fine-scale (25-m to 30-m) fuels across the landscape.

Total fuel loadings were compared across the range of fuel variables mapped. In addition, each fuel strata was compared (where possible) directly to identify potential differences in mapping philosophy across fuel loading mapping efforts.

To compare results of a new fuel map dataset to the results provided through SEMIP, the above test cases can be used. Perimeters used are stored in the SEMIP Data Warehouse (Appendix A).

We recommend that researchers and fire managers pay attention to what attributes are mapped and what the original purposes of the mapping were, as most fuel loading maps are not created for smoke emissions purposes. Fuel loading maps prepared for fire behavior analysis or fire danger rating do not contain the full suite of fuels attributes required for modeling smoke emissions. Moreover, these types of fuel loading maps were not built for actually measuring biomass across a landscape. Fuel loading maps were designed as inputs to fire behavior models and were adjusted so that for a particular vegetation type the appropriate fire behavior was simulated. Fuel loading maps likely do not provide an accurate representation of the actual overall fuels on the landscape. For smoke emissions modeling, researchers should consider the use of more inclusive fuel loading mapping systems such as the FCCS or the FLM/LANDFIRE map layers, as these maps were designed to represent fuels for estimating fuel consumption and smoke emissions.

See also:

- On Tripod case fuels: Drury et al. (2012)
- On fire emissions inventory comparisons: Larkin et al. (2012)

D.3 TOTAL CONSUMPTION

Fuel Consumption can be split into two categories: total fuel consumption and fuel consumption over time (Time Profile of Consumption). This is done because Total Consumption is generally easier to model and to predict than the specific hourly or sub-hourly Time Rate of Consumption. This division also facilitates the recognition that data available for Total Consumption is significantly greater than for the Time Rate of Consumption; to obtain Total Consumption numbers pre- and post-burn plots can be utilized.

Contained within Total Consumption is a recognition of *fire phase*. SEMIP uses the labeling found within the CONSUME model, dividing overall consumption into *flaming, smoldering,* and *residual* phases. The residual phase is sometimes given other labels and can be thought of as longer-term consumption, with flaming and smoldering being shorter in duration. Division of Total Consumption into phases is important because of the differences in efficiencies and emitted species occurring during these different phases. Thus a consumption model's ability to correctly model the various total consumption numbers for each phase will directly affect the ability of the overall system to correctly predict emissions, notably of fine-scale particulate matter ($PM_{2.5}$).

Total consumption used in fire emissions and smoke impact modeling is generally:

- Total fuel consumed
- Total fuel consumed by fire phase (flaming, smoldering, residual)

Hourly consumption/emissions numbers are necessary for modeling fire beyond total emissions; the time rate of consumption is dealt with in the next section.

Because total consumption information can come from observational pre- and post-burn plot data (where available), high quality datasets do exist. Many observational datasets have been previously used to evaluate and calibrate common consumption models such as CONSUME and FOFEM. Issues with overall total consumption models are generally ones of:

- Extrapolation from observed/calibrated conditions to other conditions
- Different underlying dependencies (e.g., on fuel moistures and the distribution of fuel strata)
- Sensitivity to underlying dependencies (e.g., on fuel moistures and the distribution of fuel strata)
- Compatibility with the available fuel strata information
- Difficulties with and/or simplistic assumptions for modeling specific types of consumption (e.g., canopy, shrubs, deep organics)

Consumption information can be stratified by:

- Geographic region

- Ecosystem or vegetation type
- Type of fire
- Fuel moisture conditions

Because of this, analyses must be tailored to examine regional, vegetative, fuel moistures, and type of fire differences.

D.3.1 Identified Potential Analyses:

Cross-comparison of consumption models and observed consumption showing:

- Basic statistics (mean/median, quartiles, peak)
- Non-normal statistics (consumption can be highly skewed across fuel loading)
  - by Fuel Strata
  - by Fire Type:
    - Unplanned ignition
    - Planned ignition
  - by Regional categorization:
    - All (e.g., CONUS)
    - Geographic region (e.g., Northwest, Southeast, etc.)
  - by Vegetation Type
  - by Fuel Moisture conditions

Examples of data that can be used to meet these analysis needs are:

- Plots: specific campaigns done to investigate total fuel consumption (e.g., Fire and Environmental Research Applications Team); long-term research forests / plots that experience fire (e.g., Tall Timbers, FIA plots, or Long Term Ecological Research (LTER) plots)
- Maps: Forest assessment maps
- Satellite: LANDSAT, MODIS burn scar / intensity; GOES / MODIS radiance

D.3.2 Analyses Performed in Phase 1

Test cases used (see Appendix B):

- Fires Everywhere
- 2008 National Emissions Inventory (NEI)
- 2006 Tripod Complex (Tripod)
- 2007 Bugaboo Complex (Bugaboo)
- additional fuel moisture sensitivity study

Scales examined:

- Fires Everywhere: 1-km grid over CONUS
- NEI: 30-m fuels aggregated for large fire areas for all of 2008
- Tripod/Bugaboo: 25-m/30-m and 1-km fuels statistically aggregated to fire area

Datasets/models used (see Appendix C):

- *in addition to fuel loading models listed in Appendix D.2.2*
- EPM v 1.0 (Fires Everywhere)
- FEPS v1.1 (Fires Everywhere)
- Consume v3.0 (Fires everywhere)
- Consume v4.0 (NEI, Tripod, Bugaboo)
- FOFEM v 5.7 (Fires everywhere, NEI, Tripod, Bugaboo)
- FINN (NEI)
- FLAMBE (NEI)

Model pathways examined:

- *Fuels > Consumption*
- NFDRS 1-km > EPM v 1.0 (Fires Everywhere)
- NFDRS 1-km > FEPS v1.1 (Fires Everywhere)
- NFDRS 1-km > Consume v 3.0 (Fires Everywhere)
- NFDRS 1-km > FOFEM v 5.7(Fires Everywhere)
- Hardy98 1-km > EPM v 1.0 (Fires Everywhere)
- Hardy98 1-km > FEPS v1.1 (Fires Everywhere)
- Hardy98 1-km > Consume v 3.0 (Fires Everywhere)
- Hardy98 1-km > FOFEM v 5.7(Fires Everywhere)
- FCCS v1 1-km > EPM v 1.0 (Fires Everywhere)
- FCCS v1 1-km > FEPS v1.1 (Fires Everywhere)
- FCCS v1 1-km > Consume v 3.0 (Fires Everywhere)
- FCCS v1 1-km > Consume v 4.0 (NEI)
- FCCS v1 1-km > FOFEM v 5.7(Fires Everywhere)
- FCCS-LF 1km > Consume v 3.0 (NEI, Tripod, Bugaboo)
- FCCS-LF 1km > FOFEM v 5.7(NEI, Tripod, Bugaboo)
- FCCS-LF 30-m > Consume v 4.0 (NEI, Tripod, Bugaboo)
- FCCS-LF 30-m > FOFEM v 5.7(NEI, Tripod, Bugaboo)
- LANDFIRE 30-m > Consume v 4.0 (NEI, Tripod, Bugaboo)
- LANDFIRE 30-m > FOFEM v 5.7(NEI, Tripod, Bugaboo)
- Ok-Wen 25-m > Consume v 4.0 (Tripod)
- Ok-Wen 25-m > FOFEM v 5.7(Tripod)
- FINN 1-km > FINN Fuel Consumption (NEI)
- FLAMBE 30-arc second > FLAMBE Fuel Consumption (NEI)

Model inputs:

- In addition to the fuel loadings specified above, fuel moistures and other specific consumption model inputs (e.g., canopy consumption) were specified for each test case. See the individual test case descriptions in Appendix B for more information.

Variables examined:

Analysis Type	Test Case	Variables Examined (where available)
National annual totals	NEI	*Totals summed as tons and tons/acre* Total Fuel Consumed Total Surface Fuel Consumed Total Woody Fuel Consumed Total Sound Woody Fuel Consumed Total Rotten Woody Fuel Consumed Total Canopy Consumed
1-km "pixel" locations	Fires Everywhere	*all as tons/acre* Total Downed Woody Fuel Consumed Canopy Fuel Consumed Shrub Fuel Consumed Grass Fuel Consumed Duff Fuel Consumed 1-hr Fuel Consumed 10-hr Fuel Consumed 100-hr Fuel Consumed 1000-hr Fuel Consumed 10000-hr Fuel Consumed 10000-hr+ Fuel Consumed
Fire level comparisons	Tripod Bugaboo	*Aggregate total over all grid cells in the fire area (in tons):* Total Fuel Consumed *Statistics done on fuel strata for all grid cells within the fire area (in tons/acre):* Total Fuel Consumed Total Surface Fuel Consumed Total Woody Fuel Consumed Total Sound Woody Fuel Consumed Total Rotten Woody Fuel Consumed Canopy Fuel Consumed Stump Fuel Consumed Shrub Fuel Consumed Grass/Forb Fuel Consumed Litter Fuel Consumed Duff Fuel Consumed

Note: not all variables were available for all model pathways because of differences in the fuel loading datasets; see Appendix D.2.2 "Variables Examined" table for available variables per fuel loading dataset.

Analysis Summary:

Analyses were conducted similarly to the fuel loading analyses. For the Fires Everywhere case, individual 1-km pixels were compared across CONUS. For the NEI case, totals were produced for all areas within MTBS large fire perimeters for 2008. For the Tripod and Bugaboo cases, statistics were done on the consumption numbers to look at overall distributions over the fire area.

In general, both Consume and FOFEM were run for each fuel loading dataset. The exceptions were FINN and FLAMBE, where consumption was calculated within each system. NFDRS and Hardy98 fuel loadings were used for the Fires Everywhere and Tripod cases for historic reasons. FEPS and EPM consumption was calculated for the Fires Everywhere case, but generally not used in other cases, as Consume and FOFEM supersede these older models.

Significant variability between model pathways was found in each test case, but the overall differences between Consume and FOFEM were small compared with the differences in switching fuel loading databases (see Section 4.2.3).

A fuel moisture sensitivity study was done on the Consume model to determine overall potential sensitivity to varying fuel moistures. Fuel moistures were held constant for the Fires Everywhere case but set at values derived for the period of the individual fires for the NEI, Tripod, and Bugaboo cases (see the individual test case descriptions in Appendix B).

See also:

- On Tripod case consumption comparisons: Drury et al. (2012)
- On national annual consumption and emissions comparisons: Larkin et al. (2012)
- On improving national emissions inventories: Larkin et al. (2010)

D.4 TIME PROFILE OF CONSUMPTION

The time profile of consumption here refers to the hourly growth rate (as measured in consumption or emissions) of the burn. It is one of the least recorded parts of the fire emissions and smoke impact modeling chain. In general, there is more information available for prescribed fires than for wildfires. Depending on the model, time rates may be given in consumption, emissions, consumption by fire phase, and/or emissions by fire phase.

In principle, the time rate of growth of a fire (in either consumption or emissions terms) can be derived from a fire growth model. However, coupling of fire emissions / smoke impact modeling with a fire growth model is only rarely done for several reasons:

- Computational cost of fire growth modeling
- Uncertainties in fire growth modeling
- Mismatches between fire growth models utility (that may be directed at the maximum possible growth for fire-fighter safety) and the needs of fire emissions / smoke impact modeling (that need accurate fuel consumption information)

Time profile of consumption information used in fire emissions and smoke impact modeling is generally:

- Per hour rates of fuel consumed by fire phase (flaming, smoldering, residual) *or* per hour rates of emissions

Because timing of fire consumption is different depending on whether the fire is a prescribed fire or a wildfire, analyses of time rates must be done separately for:

- Prescribed burns
  - o Separately by prescribed burn type (broadcast burns, piles, etc.)
- Wildfires

D.4.1 Identified Potential Analyses:

Cross-comparison of fire detection systems and observed / reported fire information showing:

- Time series statistics
- By Type of fire:
  - o Prescribed fires
  - o Wildfires
- Potentially by region

Examples of data that can be used to meet these analysis needs are:

- Specific Ground Field Measurements: video (including infrared), tracer studies
- Satellite: GOES radiance (only satellite capable of fast enough measures)
- Aircraft: Time series hyperspectral imagery

D.4.2 Analyses Performed in Phase 1

Test cases used (see Appendix B):

- Naches Prescribed Fire

Scales examined:

- Hourly data over a several day period for each fire

Datasets/models used (see Appendix C):

- For wildfire: WRAP Time Profile plus variants

Modeling pathways examined:

- Overall modeling system (for Naches prescribed fire information):
  Fuels > Consumption > Time Profile > Emissions >
  ... Plume Rise > Dispersion
  FCCS-LF 1-km > Consume v 3.0 > > FEPS v1.1 > FEPS v.1.1 *w/variants* >
  … FEPS v1.1 > HYSPLIT
- Overall modeling system (for prescribed fire (Naches) simulated as a wildfire):
  Fuels > Consumption > Time Profile > Emissions >
  ... Plume Rise > Dispersion
  FCCS-LF 1-km > Consume v 3.0 > > FEPS v1.1 > WRAP *w/variants* >
  … FEPS v1.1 > HYSPLIT

Variables examined:

Analysis Type	**Test Case**	**Variables Examined**
Smoke Concentration Sensitivity	Naches Prescribed Fire;	Surface $PM_{2.5}$ Concentrations by Hour *Overall statistical aggregates:* *max, ave, sum* *timing of max concentration* *Overall and by hour:* *number grid cells > 0.1 ug/m3* *number grid cells > 10 ug/m3* *number grid cells > 20 ug/m3* *number grid cells > 35 ug/m3*

Analysis Summary:

In theory, hourly emissions from wildfires are based on fire behavior, meteorological conditions, topography, and fuels. However, it is common practice to utilize simple time profiles to allocate consumption and emissions throughout the day.

Commonly used for wildfires, the WRAP derived profile (see Section C.4.1) was produced by the Western Regional Air Partnership (WRAP, 2002) and describes the diurnal distribution of emissions based on consumption. This diurnal consumption profile was based on consensus expert knowledge of wildfire behavior in the western U.S., where fire behavior would begin to increase in the morning, reach a peak in the mid-afternoon (1600 hours local time), and then decay into the evening. Over 90% of the emissions occur over a 10-hour period

Currently data do not exist to evaluate this WRAP diurnal profile, and therefore a sensitivity analysis was conducted to determine the impacts of this modeling step on surface $PM_{2.5}$ concentrations. The WRAP time profile was shifted earlier and later in the day, and altered to make it more “peaked” with more of the emissions in a narrower widow and more "flat" with more of the emissions in a broader band throughout the day. The time shifts were done without alteration to the profile itself. Six altered profiles were created by compressing the WRAP time profile in towards its existing maximum hour, or by spreading the existing curve out from its existing maximum hour (Figure D1). The curves are labeled by their relative peak value as compared with the original WRAP time profile curve – 50%, 66%, 80%, 90%, 100% (original), 110%, 125%, 150%, and 200%.

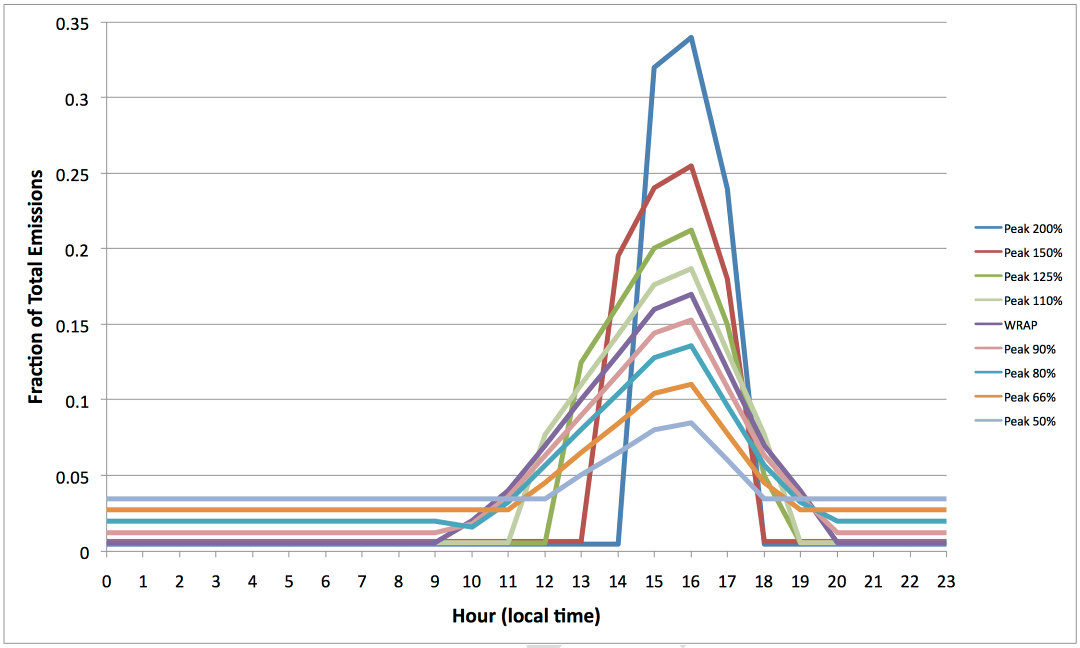


Figure D1. The altered WRAP time profile curves. The curves are labeled by their relative peak value compared with the original WRAP profile (also shown).

For prescribed fires, emissions are distributed according to the exponential decay algorithm in the FEPS model, and emissions are further separated out by fire phase; flaming, smoldering, and long-term smoldering. Three cases were simulated for this sensitivity analysis: the default case (FEPS) where fire ignition occurred at 1PM local time; fire ignition moved three hours earlier (FEPS_3hE); and fire ignition moved two hours later (FEPS_2hL). The timing of the prescribed fire also influenced the modeled duration of each of the three fire phases and thus how emissions were allocated over that duration. For example, an earlier ignition yielded a longer duration fire, which had a lower percentage of emissions per hour. And vice versa, a later ignition time yielded a shorter duration fire, which had a higher percentage of emissions per hour, perhaps due to sundown times. Figure D2 shows the three prescribed fire diurnal consumption profile curves of consumption for the three phases of each fire.

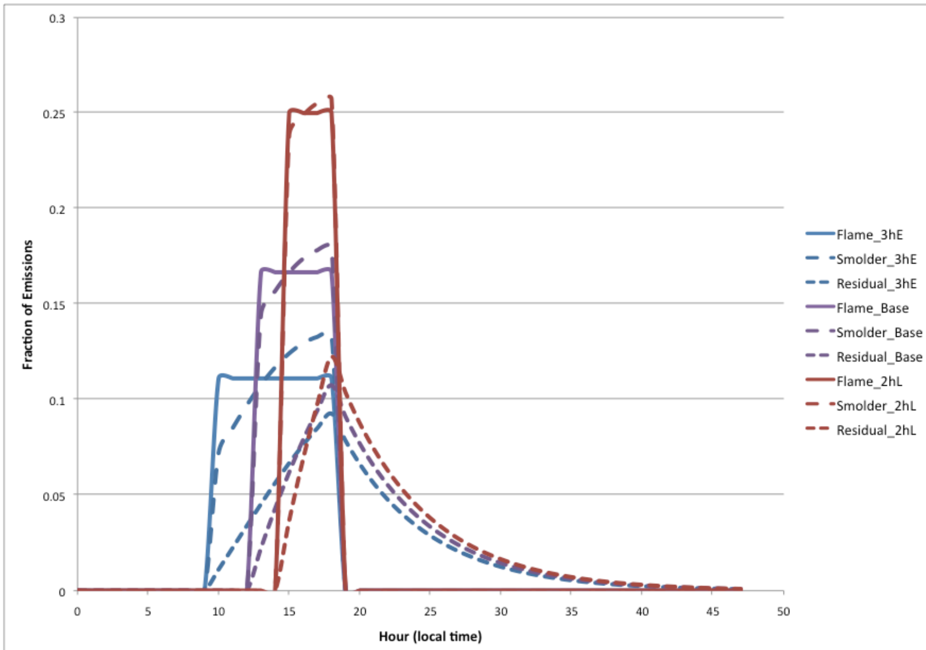


Figure D2. Time profile of how emissions are allocated for a prescribed fire by FEPS for three cases: 1) the Naches RX fire ignited at 10 am PDT (3hE, blue), 2) the Naches RX fire ignited at 1 pm PDT (Base, purple), and 3) the Naches RX fire ignited at 3 pm PDT (2hL, red). Solid lines indicate the flaming phase, large dashed lines indicate the smoldering phase, and small dashed lines indicate the long-term smoldering phase.

Six metrics were calculated to investigate the spatial and temporal impacts that the nine wildfire and three prescribed fire diurnal consumption profile curves had on the modeled domain one-hour $PM_{2.5}$ concentrations. The parameters were: maximum $PM_{2.5}$ concentration, total $PM_{2.5}$ concentration, and count of grid cells having a concentration greater than a threshold, for four thresholds: > 0.1 μg/m^3, > 10 μg/m^3, > 20 μg/m^3, and > 35 μg/m^3. These metrics were calculated for 1) the entire domain for all times, 2) the entire domain per hour, and 3) each grid cell for all hours. In this way the spatial and temporal scale of smoke impacts (i.e., hourly $PM_{2.5}$ concentrations) could be investigated for the various diurnal consumption profiles. Results indicate that the modeled time profile and modeled planetary boundary layer interact to produce higher or lower surface concentrations. This interaction magnifies the need for a more complete understanding of the time-rate of emissions. Results for this step can be found in Sections 4.1.2 (sensitivity analysis) and 4.2.4 (comparison to satellite observations).

D.5 EMISSIONS

Emissions can be split into two categories: total emissions and emissions over time. In order to model plume rise and smoke impacts, emissions (including heat) over time (e.g., hourly) are needed.

Emissions information used in fire emissions and smoke impact modeling is generally:

- Total emissions (for fire emissions calculations)
- Emissions by hour (for smoke impact modeling)

Common emissions utilized are:

- Heat (often not considered an emission) for plume rise
- $PM_{2.5}$, PM_{10} for particulate matter modeling
- CO_2, CH_4 for greenhouse gas accounting
- NO_x, SO_2, NMHC, VOCs for atmospheric chemical modeling

As discussed in the Time Profile of Consumption section (Appendix D.4), significant assumptions are generally made in assigning fire consumption and emissions rates over time. We treat these uncertainties and assumptions and their implications within the Time Profile of Consumption output level; here we focus on total emissions.

Many common emissions models (e.g., CONSUME, FOFEM, FEPS) use similar emissions factors. Other modeling systems (e.g., FINN) use more modern emissions factors. Objectively it is difficult to assess which is correct, given that smoke concentrations are only related to emissions through the dispersion and plume rise modeling steps.

Because emissions come from the application of emissions factors, issues with overall total emissions are generally ones of:

- Uncertainties in emissions factors due to low numbers of observations
- Uncertainties in applying emissions factors due to unknown fire consumption efficiency / fire phase segregation
- Uncertainties in the influence of fuel layer consumption on emission factors

Emissions factors are often listed by:

- Total for a fire, Fire phase, or consumption efficiency
- Vegetation type

For this reason is it useful to tailor analyses by:

- Fire phase or Combustion Efficiency
- Fire type (as this affects fuel consumed)
- Vegetation type
- Fuel moisture conditions (as this affects fuel consumed)
- Region

D.5.1 Identified Potential Analyses:

Cross-comparison of emissions showing:

- Basic statistics (mean/median, quartiles, peak)
- by Vegetation Type
  - especially for regional issues like deep organic layer consumption
- by Fire Type:
  - Unplanned ignition
  - Planned ignition

- by Regional categorization:
    - o All (e.g., CONUS)
    - o Geographic region (e.g., Northwest, Southeast, etc...)
- by Fuel Moisture conditions
- by Fire Phase or Combustion Efficiency

Examples of data that can be used to meet these analysis needs are:
- Lab experiments
- Specialized field in-situ measurements (on wildfires or prescribed fires)

D.5.2 Analyses Performed in Phase 1

Test cases used (see Appendix B):
- 2008 National Emissions Inventory (NEI)
- 2006 Tripod Complex (Tripod)
- 2007 Bugaboo Complex (Bugaboo)
- emissions factor literature review study and comparison to FEPS emission factor calculation

Scales examined:
- NEI: 30-m aggregated for large fire areas for all of 2008
- Tripod/Bugaboo: 25-m/30-m and 1-km depending on fuels information statistically aggregated to fire area

Datasets/models used (see Appendix C):
- *in addition to fuel loading models listed in Appendix D.2.2*
- Consume v4.0 (NEI, Tripod, Bugaboo)
- FOFEM v 5.7(NEI, Tripod, Bugaboo)
- FINN (NEI)
- FLAMBE (NEI)
- FEPS v1.1 emission factor equations (used to compare to literature emission factors)

Model pathways evaluated:
- *Fuels > Consumption > Emissions*
- NFDRS 1-km > Consume v4.0 > Consume v4.0 (Tripod, Bugaboo)
- NFDRS 1-km > FOFEM v 5.7> FOFEM v 5.7(Tripod, Bugaboo)
- Hardy98 1-km > Consume v4.0 > Consume v4.0 (Tripod, Bugaboo)
- Hardy98 1-km > FOFEM v 5.7> FOFEM v 5.7(Tripod, Bugaboo)
- FCCS v1 1-km > Consume v4.0 > Consume v4.0 (NEI, Tripod, Bugaboo)
- FCCS v1 1-km > FOFEM v 5.7> FOFEM v 5.7(NEI, Tripod, Bugaboo)
- FCCS-LF 1km > Consume v4.0 > Consume v4.0 (NEI, Tripod, Bugaboo)
- FCCS-LF 1km > FOFEM v 5.7> FOFEM v 5.7(NEI, Tripod, Bugaboo)
- FCCS-LF 30-m > Consume v4.0 > Consume v4.0 (NEI, Tripod, Bugaboo)
- FCCS-LF 30-m > FOFEM v 5.7> FOFEM v 5.7(NEI, Tripod, Bugaboo)
- LANDFIRE 30-m > Consume v4.0 > Consume v4.0 (NEI, Tripod, Bugaboo)
- LANDFIRE 30-m > FOFEM v 5.7> FOFEM v 5.7(NEI, Tripod, Bugaboo)

- Ok-Wen 25-m > Consume v4.0 > Consume v4.0 (Tripod)
- Ok-Wen 25-m > FOFEM v 5.7> FOFEM v 5.7(Tripod)
- FINN 1 km > FINN > FINN (NEI)
- FLAMBE 30-arc second > FLAMBE > FLAMBE (NEI)

Model inputs:

- In addition to the fuel loadings specified above, fuel moistures and other specific consumption model inputs (e.g., canopy consumption) were specified for each test case. See the individual test case descriptions in Appendix B for more information.

Variables examined:

Analysis Type	**Test Case**	**Variables examined**
National annual totals	NEI	*in tons and tons/acre* Total CO_2, CO, CH_4, $PM_{2.5}$, and PM_{10} emissions
Fire level comparisons	Tripod Bugaboo	*Aggregate total over all grid cells in the fire area (in tons):* Total CO_2, CO, CH_4, NMHC[a], NOx[b], SO_2[b], $PM_{2.5}$, and PM_{10} Emissions *Statistics done on fuel strata for all grid cells within the fire area (in tons/acre):* Total CO_2, CO, CH_4, $PM_{2.5}$, PM_{10}, NMHC, NO_x, and SO_2 Emissions Flaming CO_2, CO, CH_4, $PM_{2.5}$, PM_{10}, NMHC, NO_x, and SO_2 Emissions Smoldering CO_2, CO, CH_4, $PM_{2.5}$, PM_{10}, NMHC, NO_x, and SO_2 Emissions Residual CO_2, CO, CH_4, $PM_{2.5}$, PM_{10}, NMHC, NO_x, and SO_2 Emissions
Vegetation type	Emission Factor Review	*in kg emitted per kg of fuel consumed* Emission factors of CO_2, CO, CH_4, and $PM_{2.5}$

[a]Consume only
[b]FOFEM only

Variables available (black indicates availability):

Species	**Consume**	**FOFEM**	**FEPS**	**FINN**	**FLAMBE**
CO_2, CO, CH_4, $PM_{2.5}$,	■	■	■	■	■
PM_{10}	■	■		■	■
NMHC	■				
NOx		■			
SO_2		■			

Analysis Summary:

Because of the general lack of observational emissions, data inverse methods were attempted to back out constraints on emissions and plume injection height from ground smoke measurements. These methods did not produce statistically robust results and are excluded here.

Analyses were conducted similarly to the fuel loading analyses. For the Fires Everywhere case, individual 1-km pixels were compared across CONUS. For the NEI case, totals were produced for all areas within MTBS large fire perimeters for 2008. For the Tripod and Bugaboo cases, statistics were done on the consumption numbers to look at overall distributions over the fire area.

Both Consume and FOFEM emissions were computed for each fuel loading dataset. Consume emissions factors were used to estimate smoke production when Consume was used as the consumption model. FOFEM emissions factors were used when FOFEM was used to estimate fuel consumption. The exceptions were FINN and FLAMBE where consumption was calculated within each system. Emissions were compared for species that were produced by all models (see Variable table above). NMHC (from Consume), NO_x, and SO_2 (both from FOFEM) were not intercompared because these were produced by only one model.

Emission results were dependent upon the fuel and consumption model choices. In addition, the static emission factors were different in each model, resulting in different emissions for a given quantity of fuel consumed (see C.5.2 and C.5.3).

An emissions factor literature review was done to examine newer emissions factors published between 1984 and 2010. See Section 4.2.5 for more information.

See also:

- Drury S.A., Larkin N.K., Raffuse S.M., Strand T.M., Huang S-M. (2012) Uncertainty in Smoke Emissions Modeling: The Tripod Fire Complex. *Ecological Modeling* (in prep.)
- Strand, T. M., Larkin, N., O'Neill, S. M., Peterson, J., and Martinez, N. (2012) A synthesis and review of wildland fire emission factors for smoke modeling applications in the United States. *J. Geophys Res*. (in prep.)

D.6 PLUME HEIGHT

Plume height is defined here as the vertical zone in which a buoyant plume begins to transport horizontally away from its source. Plume heights are critical for determining which layer of the atmosphere will transport and disperse smoke. Modeling plume heights requires knowledge of both the fire and its activity (both heat and emissions) and the atmosphere near the fire. Additionally, details of the organization of the plume as it lofts is important to entrainment and convective column formation, although this information is often not known *a priori*.

Plume height information used in fire emissions and smoke impact modeling is generally:

- Plume top and plume bottom
- Vertical profile of emissions

Because plume heights and vertical profiles of emissions are highly dependent on the fire itself and on the atmospheric conditions, the issues with plume heights are generally ones of:

- Not knowing how the plume is organized (e.g., how many convective columns or "cores")
- Utilizing plume rise models developed for much simpler situations like smokestacks
- Uncertainties in emissions and heat and their time profile
- Uncertainties and errors in the modeled atmospheric conditions
- Observations that only mark one part of the plume (e.g., plume top) but cannot get the full vertical profile

Observed plume heights are generally from remote sensing, and so issues with plume height observations are generally ones of finding observations of plumes rather than of regional coverage.

Plume height calculations can vary considerably in quality as upstream information is available (e.g., fire size information, planned ignition patterns for prescribed fire, observed fuel consumption). Therefore, analysis of plume heights can be stratified on the basis of available upstream information. In general, plume height calculations should also be examined on the basis of fire size and daily growth as questions pertain to how well plume height models work over the large range of observed fire sizes.

D.6.1 Identified Potential Analyses:

Cross-comparison of plume height models and observed / reported fire information showing:

- Basic statistics (mean/median, quartiles, peak)
- by Size categorization:
- by Type categorization:
    - Unplanned ignition
    - Planned ignition
- by Regional categorization:
    - All (e.g., CONUS)
    - Geographic region (e.g., Northwest, Southeast, etc...)
- By Fire Behavior (where known)

Examples of data that can be used to meet these analysis needs are:

- Ground: LIDAR field data, cameras, inclinometers
- Aircraft: From in-situ campaigns
- Satellite: CALIPSO, MISR

D.6.2 Analyses Performed in Phase 1

Test cases used (see Appendix B):
- Multi-year plumes

Scales examined:
- Multi-year plumes: individual fires aggregated by size of fire, region, etc…
- Satellite measurements are instantaneous overpass measurements
- Modeled plumes are hourly data

Datasets/models used (see Appendix C):
- CALIPSO-derived plume tops
- MISR wind corrected median plume top heights
- FEPS modeled plume heights

Modeling pathways examined:
- Plume heights from real-time prediction system using:
  Fire info > Fuels > Consumption > Time Profile > Emissions > Plume Rise
  SmartFire v1 real-time > FCCS v1 > Consume v3.0 > WRAP > FEPS v1.1 > FEPS v1.1

Variables examined:

Analysis Type	Test Case	Variables Examined
Fire by fire comparisons	Multi-year plume case	Plume top height (m AGL)

Analysis Summary:

Because of the sparseness of measurements available to assess plume rise, a special test case was created to take advantage of all available space-based observation data. A plume rise dataset of satellite based observations was collected and compared to the predictive real-time smoke modeling system modeled plume heights.

Additional modeling pathways need to be modeled to see how sensitive the results are to model choice.

See also:

- Raffuse, S.; Craig, K.; Larkin, N.; Strand, T.; Sullivan, D.; Wheeler, N.; Solomon, R. 2012. An evaluation of modeled plume injection height with satellite-derived observed plume height. *Atmosphere, 3*, 103-123.

D.7 GROUND SMOKE CONCENTRATIONS

Ground concentrations are a final output of the emissions and smoke impact modeling pathway. The ability of this modeling step to produce good results relies on the previous modeling steps, which are used to characterize the emissions from the fire-source. Ground concentration datasets observed within a smoke plume are available, but are surprisingly scarce for some atmospheric gasses and particulates. Observation datasets (of ozone, $PM_{2.5}$, NO_x, and CO) are usually collected by existing air-quality monitoring networks such as AirNow-Tech or IMPROVE. These networks can be sparse in many regions of the country where smoke impacts are prevalent (e.g., Northern California). Rapidly deployed networks are used by the U.S. Forest Service and other state and federal agencies to collect within-plume smoke concentrations during wildfire events that produce large smoke impacts in regions of sparse monitoring. The U.S. Forest Service recently did several campaigns that collected $PM_{2.5}$ surface concentrations within smoke plumes in the Western U.S. (Strand et al., 2012).

Smoke concentration information used in fire emissions and smoke impact modeling is generally:

- Hourly surface concentrations of $PM_{2.5}$ ($\mu g/m^3$)
- Ozone (ppb), NO_x (ppb), CO (ppm) can also be used to examine smoke impacts

Hourly data is commonly collected and used for model result evaluation. In some cases, 8-hour or 24-hour averages are preferable for the analyses. Note that both observed and modeled sub-hourly smoke concentrations are generally not available, although such information would be useful in examining smoke transport during short-duration fires (i.e., prescribed fires) or during transition phases of the fire (i.e., when a surface fire becomes an aerial, canopy fire).

Because surface concentrations are generally collected through monitoring systems (either existing networks or deployed during the event), the issues with observations of surface concentrations are:

- Coverage (spatial and temporal)

- Density of the network and number of monitors within the network
- Monitor problems with high smoke concentrations
- Sources of error from the observations themselves due to monitor location, mechanical difficulties, and data downloading processes (manual or electronic upload)

There are satellite-based products that derive surface concentrations from total column observations. These have known associated errors and issues such as clouds blocking the view of the instrument and elevated smoke measured by satellite but not present on the ground.

Surface concentrations of the primary air quality pollutants ($PM_{2.5}$, ozone, CO, NO_x, and PM_{10}) are usually available from the in-situ networks around the country. Concentrations of trace gasses and air toxics are difficult to obtain. Analyses can be tailored to:

- Country
- Region
- State
- Geographic terrain (i.e., narrow valley)
- Airshed

As well as the:

- Type of fire
- Fire size
- Management action involved
- Atmospheric chemical species of concern (i.e., $PM_{2.5}$)

In addition to the above analysis, sensitivity tests were done to determine the overall sensitivity of ground smoke concentrations to the modeling pathway for the Naches test case. Additionally, inverse analyses and other techniques were investigated to leverage ground smoke concentrations into bounds on earlier aspects of the modeling chain (specifically time profile and plume rise), but these ultimately proved unsuccessful.

D.7.1 Identified Potential Analyses:

Analyses of modeled surface concentrations with observations and intercomparisons of model-to-model surface concentration results:

- Basic statistics (mean/median, quartiles, peak)
- Performance metrics (mean fractional bias, mean fractional error, root mean square error, other variants of the bias and error metric)
- Probability of detection and false alarm metrics
- Data distribution
- Location relative to:
    - Fire location
    - Terrain
    - Urban centers
    - Meteorology (meso-scale such as a front or local-scale such downslope flow)

Examples of data that can be used to meet these analysis needs are:

- Ground: Ozone, $PM_{2.5}$, CO, NO_x, etc., from AirNow-Tech and IMPROVE networks, $PM_{2.5}$ data from U.S. Forest Service Rapid Response deployed networks
- Satellite: AIRS total column CO, AIRS total column ozone, OMI tropospheric column NO_2, MODIS aerosol optical depth (AOD)

D.7.2 Analyses Performed in Phase 1

Test cases used (see Appendix B):

- 2007/2008 Regional California Wildfires (Cal)
- 2009 Naches Prescribed Fire (Naches)

Scales examined:

- Regional to local (down to 1.33-km for Naches case)
- Hourly to multi-day averages

Datasets/models used (see Appendix C):

- For California case:
    - AirNowTech $PM_{2.5}$ data (2007, S. California)
    - U.S. Forest Service Rapid Response $PM_{2.5}$ data (2008, N. California)
    - CMAQ modeled $PM_{2.5}$ surface concentrations from BlueSky Gateway (see section B.3)

Modeling pathways examined:

- Sensitivity analyses done using:
    - Overall modeling system (for Naches prescribed fire information):
Fuels > Consumption > Time Profile > Emissions >
... Plume Rise > Dispersion
FCCS-LF 1-km > Consume v4.0 > > FEPS v1.1 > FEPS v.1.1 >
… FEPS v1.1 > HYSPLIT
    - Overall modeling system (for Naches as wildfire):
Fuels > Consumption > Time Profile > Emissions >
... Plume Rise > Dispersion
FCCS-LF 1-km > Consume v4.0 > > FEPS v1.1 > WRAP >
… FEPS v1.1 > HYSPLIT
    - Each component of above modeling chain, except Dispersion was done with variants (see below).

- Surface concentrations from real-time prediction system using:
Fire info > Fuels > Consumption > Time Profile > Emissions >
.... Plume Rise > Dispersion
SmartFire v1 real-time > FCCS v1 > Consume v3 > FEPS v1.1 > WRAP >
.... FEPS v1.1 > CMAQ

Variables examined:

Analysis Type	**Test Case**	**Variables Examined**
Smoke Concentration Sensitivity	Naches Prescribed Fire	Surface $PM_{2.5}$ Concentrations by Hour *Overall statistical aggregates:* *max, ave, median, sd* *timing of max concentration* *Overall and by hour:* *number grid cells > 0.1 ug/m3* *number grid cells > 10 ug/m3* *number grid cells > 20 ug/m3* *number grid cells > 35 ug/m3* *distance to max concentration*
Smoke predictions	Cal	Surface $PM_{2.5}$ Concentrations by Hour Observed vs. Predicted *Mean fractional bias, fractional bias* *Mean fractional error* *Maximum, median, minimum* *Data distribution* *Gradient between monitoring sites and their respective grid cells*

Analysis Summary:

Sensitivity analyses of ground concentrations to the various modeling steps in the smoke impact modeling pathway was done for the Naches test case. For this case, which was selected due to the availability of very high resolution meteorological model data (1.33-km grid spacing at 10min time resolution), changes in the overall amount, timing, and pattern of smoke concentrations were evaluated as fire information, fuel loadings, total consumption, total emissions, time profile, and plume rise were artificially modified through a number of variants. Additionally, separate modeling sensitivity studies were done treating the fire as a prescribed fire (as actually occurred) and as a wildfire. The results show significant sensitivities to all aspects of the modeling chain, and differential sensitivity of various metrics (maximum surface concentration, timing of the maximum surface concentration, overall surface smoke, etc.) to various aspects of the modeling chain. See Section 4.1.2 for more details.

Surface $PM_{2.5}$ concentrations predicted in real time by the BlueSky Gateway during the 2007 Southern California wildfires and the 2008 Northern California wildfires were evaluated with observations. Prediction performance was dependent on the synoptic meteorology for the 2007 portion of the test case and on monitor location relative to local terrain type for the 2008 portion.

During the 2007 event, when the synoptic meteorology was offshore (during the Santa Ana winds) the predictions were poor (underestimated); however, when the meteorology changed to the more typical onshore flow, predictions were good. This was likely due to the mixing of the smoke throughout the boundary layer. Prediction performance was good for the 2008 wildfire event; however, when the data were parsed by location relative to their location in a narrow or broad valley, the broad valley data subset displayed better performance relative to the narrow valley subset of data.

Smoke surface $PM_{2.5}$ (and other gas and particle species) concentrations are the last output in the smoke and emission modeling pathway. Error in the previous modeling steps will propagate through to the dispersion step and into the surface concentration results. It is important to characterize fire information, fuels, combustion, emissions, time rate, and plume rise as accurately as possible. During equilibrium fire activity and well mixed atmospheric conditions, the performance of BlueSky Gateway predictions was reasonable to good. The model domain grid resolution was coarse at 36-km, and this likely played a role in the poor performance during the 2007 offshore winds. Future tests with smaller grid resolution may yield improved performance results.

See also:

- Strand, T. M., Larkin, N., Solomon, R., Rorig, N., Craig, K. J., Raffuse, S., Sullivan, D., Wheeler, N., and Pryden, D. (2012) Analyses of BlueSky Gateway PM2.5 predictions during the 2007 southern and 2008 northern California fires. *J. Geophys. Res.,* 117, D17301, doi:10.1029/2012JD017627.

D.8 TOTAL COLUMN SMOKE [deprecated for Phase 1]

Because of the availability of satellite data on aerosol optical depth (AOD) and other integrative measures of total column smoke, SEMIP identified this as a potential output level for comparison. However, other analyses were given priority and total column smoke was not examined in Phase 1.

D.8.1 Identified Potential Analyses:

Cross-comparison of different modeling pathways and meteorological dataset combinations showing with satellite measurements of AOD and smoke plume extent:

- Basic and spatial statistics

Examples of data that can be used to meet these analysis needs are:

- Ground: Stationary lidar, sun photometer
- Satellite: AOD (MODIS, GOES), aerosol index (OMI)

D.8.2 Analyses Performed in Phase 1

Not examined in Phase 1. See, for example, National Weather Service smoke forecast verification products or Larkin et al. (2009) for potential examples of total column smoke comparisons.

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FOR MORE INFORMATION

More information and resources are available through links on the project page: http://airfire.org/projects/semip. These include:

- Project updates as available;
- Updated additional reports and findings;
- Access to the Data Warehouse and Data Viewer as available;
- An updated list of published papers arising from SEMIP; and
- Links to presentations on SEMIP.

The current list of papers and documents arising from SEMIP is:

Drury S.A., Larkin N.K., Raffuse S.M., Strand T.M., Huang S-M. (2012) Uncertainty in Smoke Emissions Modeling: The Tripod Fire Complex. *Ecological Modeling* (in prep.)

Larkin N.K., Raffuse, S.M., Strand, T.M., Huang, S-M. 2012. Comparison of fire emissions inventories. *Forest Ecology and Management* (in prep.)

Larkin N.K., Strand T.M., Solomon R., Raffuse S., Drury S., Sullivan D., Wheeler, N., Chinkin L., 2010. Developing an improved wildland fire emissions inventory. 19th Annual EPA Emissions Inventory Conference, San Antonio Texas August 2010. Available at http://www.epa.gov/ttn/chief/conference/ei19/index.html

Larkin N.K, Strand T.M., Drury S.A., Raffuse S.M., Wheeler N., 2012. Final Report to the JFSP for Project #08-1-6-10: Phase 1 of the Smoke and Emissions Model Intercomparison Project. Available at http://firescience.gov.

Raffuse S., Strenfel S., Ruminski M., Larkin N.K., Hanna, J., McCarthy, M., Evaluating Fire Detection Success Rates of Satellite Detection Methods. (in prep.)

Raffuse S., Larkin, N.K., Lahm P., Du Y. (2012) Development of the wildland fire portion of the 2008 National Emissions Inventory. (in prep.)

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In addition, SEMIP results have been featured in over 20 presentations to both scientific and non-scientific audiences. See the project website for a full list.