# Critical Assessment of Wildland Fire Emissions Inventories: Methodology, Uncertainty, Effectiveness

# Final Report

# Joint Fire Sciences Program Project # 12-1-07-1


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## Background and Purpose

Fires emit a substantial amount of atmospheric pollutants (CO, CH4, non-methane organic compounds (NMOC), NOx, PM2.5), greenhouse gases (CO2, CH4, N2O), and black carbon that can have major impacts on regional air quality and global climate. In addition to being primary pollutants, the photochemical processing of $NO_X$ and NMOC leads to the formation of ozone and secondary PM2.5. The most important criteria for assessing the impacts of fires on the regional and global environment are accurate, reliable information on the spatial and temporal distribution of fire emissions (Riebau and Fox, 2010). Fire Emission Inventories (FEI) provide a spatially and temporally resolved accounting of air pollutants released to the atmosphere by wildland fires. On a national level FEI typically indicate fires as a major source of PM2.5 on an annual basis (Figure 1). However, since most fires occur during the wildfire season, the annual, CONUS wide figures greatly understate the potential impact of fire emissions on air quality. During active periods of the wildfire season, fire emissions are believed to dwarf anthropogenic sources of PM2.5 and NMOC (Figure 2), the latter of which includes hazardous air pollutants (HAP) and reactive gases that can lead to the formation of ozone and secondary PM2.5.

In the United States a primary use of FEI are air quality modeling and regulatory activities to achieve and maintain compliance with National Ambient Air Quality Standards (NAAQS) and the Regional Haze Rule (RHR). State and local air quality management agencies are responsible for developing emission control requirements to attain and/or maintain compliance with NAAQS and RHR. Air regulators need accurate inventories of fire emissions to design effective and efficient emission control strategies. Additionally, the EPA's Exceptional Events Rule (EER) provides regulatory relief for states that exceed national air quality standards because of emissions from certain sources of pollution, including wildfires and certain prescribed fires. Accurate FEI are needed by state air quality agencies to identify air pollution events attributable to wildfires.

Fire Emission Inventory Systems (FEIS) are the data aggregation and modeling systems that provide spatially and temporally resolved estimates of air pollutants released by fires. Most FEIS combine fire information and models of burnable biomass (fuel) and fuel consumption, and emission factors (EFs) to estimated emissions using a variant of the formulation proposed by Seiler and Crutzen (1980):

$$E_X = A \times B \times \alpha \times EF_X \qquad (1)$$

where the amount of a pollutant x emitted from fires ($E_x$) for a defined area and time is calculated as the product of area burned (A), fuel loading (B), the fraction of fuel consumed by fire ($\alpha$), and the emission factor for pollutant x ($EF_x$).

Over the past decade significant progress has been made in the development of FEIS. While much effort has been expended to develop and improve FEIS, the uncertainty of the systems' emission estimates are usually not reported at the spatial and temporal scales relevant to air quality modeling and management. The purpose of this project is to provide a quantitative assessment of widely used FEIS that will enable air quality and fire managers to objectively select the FEIS tools most suitable for their applications. This project has critically reviewed the algorithms, data inputs, and performance of three widely used FEIS – Global Fire Emissions Database version 4 (GFED), the Fire Inventory form NCAR (FiNN), and the Wildland Fire Emissions Information System (WFEIS).

The FEIS were also evaluated using an economic cost-effectiveness analysis. The economic component of the grant aimed at completing a cost-effectiveness analysis of fire emissions inventory systems. Initially, the economics team completed an organizational study of seven FEISs to understand the different data inputs. A complete draft comparing the organization of these seven FEISs is available. This manuscript is being updated to integrate the cost-survey results with uncertainty estimates of three FEISs in a cost-effectiveness analysis.

**Study Description**

The project addressed the following tasks:

1. Review and summarize the technical details of major FEIS.
2. Quantify the uncertainty of the components of burned area, fuel loading, and emission factors of each FEIS.
3. Quantify the uncertainty of emissions estimated by each FEIS at scales relevant to modeling ozone, PM2.5 NAAQS, and Regional Haze.
4. Compare the daily fire emissions inventories for six large wildfire events representing the dominant fire impacted ecosystems over CONUS.
5. Survey development/maintenance costs and conduct cost-effectiveness analysis for each FEIS.

**Catalogue of Wildland Fire Emission Inventory Systems**

Task 1 was addressed by creating a catalogue of FEIS. We reviewed published and unpublished (via contact with the principal investigators) technical documentation for seven FEIS used by researchers, managers, and policy makers in the U.S. (Table 1). The review summarizes and compares the framework, input data flow, input data sources, and output for the FEIS. The FEIS review produced an organizational study that has been included as a project deliverable.

**Table 1. Overview of FEIS Data Inputs.**

| FEIS | Area Burned | Fuel Loading | Fuel Consumed | Emission Factors |
|---|---|---|---|---|
| **WFEIS** | Monitoring Trends in Burn Severity Perimeters,<br>MODIS Direct Broadcast Burn Area Product | Fuel Characteristics Classification System | CONSUME,<br>Remote Automated Weather Station Data | CONSUME |
| **FETS** | NOAA Hazard Mapping System Fire Detects | Fuel Characteristic Classification System | CONSUME,<br>National Weather Service,<br>Weather Information Management System | Environmental Protection Agency AP-42 |
| **NEI** | ***SMARTFIRE 2***<br>[Monitoring Trends in Burn Severity,<br>NOAA Hazard Mapping System Fire Detects,<br>Incident Command Summary Reports] | Fuel Characteristic Classification System | CONSUME,<br>WIldland Fire Assessment System | Fire Emissions Production Simulator |
| **FINN** | MOD14,<br>MODIS Rapid Response,<br>MODIS Data Processing System | MOD12,<br>MOD44,<br>International Geosphere-Biosphere Programme Land Cover Classification | Hoelzemann et al. (2004) | Compilation of studies<br>[Andreae (2008), Andreae and Merlet (2001),<br>Akagi et al. (2011),<br>McMeeking et al. (2008)] |
| **WFEI** | MODIS Direct Broadcasting | Fuel Loading Model (modified),<br>National Fuels Photo Series,<br>Fuel Characteristics Classification System | CONSUME,<br>FOFEM,<br>North American Regional Reanalysis | Compilation of studies<br>[Coffer et al. (1990), Friedl et al. (2001), Hardy et al. (1996),<br>Nance et al. (1993),<br>Radke et al. (1991),<br>Urbanski et al. (2009),<br>Yokelson et al. (1999)] |

| FEIS | Area Burned | Fuel Loading | Fuel Consumed | Emission Factors |
|---|---|---|---|---|
| **WF_ABBA** | Geostationary Operational Environmental Satellite (GOES) WF_ABBA | MOD12,<br>MOD44,<br>MOD15 | Advanced Very High Resolution Radiometer, NOAA Global Vegetation Index | Calculated in FOFEM using data on fuel type (NOAA GAC Vegetation Condition Index) and moisture (AVHRR) |
| **GFED3** | ***GFED3***<br>[MODIS atmospherically-corrected Level 2G surface reflectance product,<br>MODIS Level 3 96-day land cover product,<br>MODIS Collection 5 version 1 Terra Climate Modeling Grid,<br>TRMM VIRS fire product,<br>ATSR World Fire Atlas (algorithm 2)] | MOD12 UMD Classification,<br>Ecoregions of the World,<br>MOD15 | Global Precipitation Climatology Project,<br>International Institute for Applied Systems Analysis,<br>GISS Surface Temperature Analysis,<br>Global Inventory Mapping and Modeling System anomalies with MODIS climatology,<br>International Satellite Cloud Climatology Project Radiative Fluxes,<br>MOD44,<br>MOD14 | Compilation of studies [Andreae and Merlet (2001), Christian et al. (2003)] |

## FEIS Uncertainty Assessment

### Reference Emissions Dataset

Two key objectives of this project were to quantify the uncertainty of data inputs (burned area, fuel loading, and emission factors) and emissions estimated of major FEIS at scales relevant to modeling ozone and PM2.5 NAAQS and Regional Haze. Accomplishment of these objectives required the development of a reference dataset of burned area, fuel loading, fuel consumption, emission factors, and emissions to serve as a baseline against which the FEIS can be evaluated. The reference wildland fire emission dataset includes daily emissions of 202 species at 250 m resolution for 2003-2012. Our reference PM2.5 emissions for 2007 and 2012 are mapped in Figure 3. The reference dataset is being submitted for publication in the U.S. Forest Service Research Data Archive (http://www.fs.usda.gov/rds/archive/). Components of the reference dataset are described below.

### Burned Area

The burned area reference dataset combined burn severity maps from the Monitoring Trends in Burn Severity Project (MTBS) (Eidenshink et al., 2007; MTBS, 2016), daily burn scar detections from the MODIS MCD64 burn scar product (Giglio et al., 2009), fire perimeters from the Geospatial Multi-Agency Coordination Wildland Fire Support archive (GEOMAC, 2014), and a comprehensive spatial wildfire occurrence database (Short, 2015). The datasets were combined to provide a geospatial dataset of burned area at a 500 m resolution for CONUS. The MODIS burn scars and active fire detections from the MODIS sensor and the GOES satellites were used to assign nominal day on which each pixel was burned. This burned area geospatial dataset served as the benchmark for evaluating the burned area datasets of the FEIS assessed in the project.

### Fuel Loading

The reference fuel loading dataset combined a forest fuel classification and fuel loading maps for rangelands (shrublands and grasslands). The spatial distribution of fuel loading was created by combining a USFS Forest Type Group map (Ruefenacht et al. 2008) and a rangeland fuels map to provide a 250 m resolution cover type map for CONUS. USFS Forest Inventory Analysis (FIA) fuel estimates from over 18,000 plots were used to assemble a new forest fuel loading classification which we have named the “fuel type groups”, or FTG. A description of the FTG fuel loading classification for the western US was published in a study that evaluated the performance and mapping of three fuel classification systems using Forest Inventory Analysis surface fuel measurements (Keane et al., 2013). For this project we have enhanced the FTG classification published in Keane et al. (2013) by 1) including coarse woody debris size distributions and decay state, variables that are critical to fuel consumption and 2) expanding coverage from the western US to all of CONUS. The FTG has 26 classes for CONUS with each class corresponding to an FIA forest type group, such as ponderosa pine group. Within each FTG class the component fuel loadings are taken as the means the FIA plot data with each FTG being derived from a few hundred to a few thousand FIA plots. The uncertainty in the fuel loading was determined using Monte Carlo simulations that sampled the underlying FIA plot data and included uncertainty of mapping errors in the USFS Forest Type Group map used in this project (Ruefenacht et al. 2008).

The rangeland fuel loading reference dataset was provided by Matt Reeves of the USFS Rocky Mountain Research Station. Reeves developed a rangeland fuel product through support by the USFS Western Wildland Environmental Threat Assessment Center. These spatially explicit data are developed using data from the Moderate Resolution Imaging Spectroradiometer (MODIS) in addition to application of unique mapping algorithms relying on site specific parameters and numerous allometric equations linking shrub structure and composition with standing biomass and fuel. Connecting surface fuel loads to natural climate drivers improves the efficacy of fire behavior, fire effects, and emissions predictions. Both herbaceous and woody components are quantified to provide a rich set of fuel bed properties. The Reeves rangeland fuels product provided pixel level estimates of herb and shrub fuel loading with uncertainties.

**Fuel Consumption**

Consumption of down dead wood, herbs, and shrubs, was simulated using the CONSUME natural fuels algorithms. Duff consumption was simulated using three of the equations employed in FOFEM, applied on a regional basis (west (Brown et al., 1985), south (Hough, 1978) and east (Reinhardt et al., 1991)). Litter consumption was estimated as 90% for all forest types and regions. The coarse woody debris and duff consumption equations require estimates of 1000 hour fuel moisture and duff moisture. Fuel moisture values were assigned to one of four moisture regimes (very dry, dry, moderate, or moist) based on 1000 hour fuel moistures from National Fire Danger Rating System stations. Duff moisture was estimated from the 100 hour moisture content using empirical equations (Harington, 1981). Burned pixels were assigned fuel moistures contents from the nearest NFDRS station. The NFRDS data was obtained from the U.S. Forest Service Wildland Fire Assessment System (WFAS) data archive (WFAS, 2014).

**Emission Factors**

The reference emission factor dataset was synthesized from a large body of emission factor studies including results a recently completed JFSP project (Project ID #08-1-6-09). The emission factor dataset has been in a special issue of Forest Ecology and Management (Urbanski, 2014). A key aspect of the synthesis that is pertinent to our project is the revelation that wildfires in forest of the western US have higher emission factors for PM2.5 and volatile organic compounds (VOC) than previously presumed based on studies of prescribed fires. It appears that most of the FEIS being evaluated in this project use outdated emission factors that may result in a significant underestimate of wildfire pollutant emissions.

**Emissions**

Best estimates and uncertainties of emission intensities (kg $m^{-2}$) for each burned pixel were derived using a Monte Carlo style analysis following the general approach outlined in the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The general approach involved randomly selecting a sample of n input values ($\mathbf{X}_i$, $\mathbf{X}_{i+1}$,…,$\mathbf{X}_n$) for the emission model (Eq. 1) and calculating the emission intensities ($\mathbf{E}_i$, $\mathbf{E}_{i+1}$,…,$\mathbf{E}_n$), where $\mathbf{X}_\mathbf{i}$ is the array of input values needed for a single emission calculation: fuel loading by component, fuel moisture, and emission factors ($EFCO_2$, EFCO, $EFCH_4$, $EFPM_{2.5}$) and $\mathbf{E_i}$ is the array of emission intensities for $CO_2$, CO, $CH_4$, and $PM_{2.5}$. Next, the mean (μ) and quantiles (q, q=.05,.10,…,.95) of the emissions were calculated ($\mathbf{E}_{\mu}$, $\mathbf{E}_{q}$). The process was repeated B times, yielding $\mathbf{E}_{\mu,1},\ldots\mathbf{E}_{\mu,B}$ and $\mathbf{E}_{q,1},\ldots\mathbf{E}_{q,B}$. Finally, mean values were calculated to provide the best estimate of emissions ($\sum_1^B E_\mu/B$) and the uncertainty ($\sum_1^B E_q/B$). B was set large enough to ensure convergence of the mean and distribution. For each sample the emission intensities were fit to a log normal probability distribution and the optimized parameters (mean and standard deviation of the distribution on the log scale) were saved. The average values of the B repetitions were taken as best estimate parameters for the probability distribution functions.

**FEIS Error Relative to Reference Emission Inventory**

The quantitative assessment of FEIS was limited to the three systems with consistent data for the 2003 – 2012 period: Global Fire Emission database, version 4 (GFED), Fire Inventory from NCAR (FINN), and the Wildland Fire Emission Inventory System (WFEIS). We have evaluated burned area (BA), fuel consumed (FC; the total biomass volatized and emitted as gases or particles), CO emitted (ECO) and PM2.5 emitted (EPM2.5). The deviation of annual and monthly emissions from the reference emission inventory (REI) were determined for the three FEIS for CONUS and Bailey ecosystem provinces. CONUS wide evaluation of annual emissions is shown in Figure 4.

We also evaluated the error of the emission inventories (relative to REI) at scales pertinent to air quality modeling for regulatory activities. The EPA recommends a model horizontal grid resolution of ≤ 12 km for ozone and PM2.5 NAAQS and of 36 km for regional Haze (US EPA, 2007). The spatial resolutions, $\Delta X$, of the FEIS are $\Delta X = 1$ km for FINN and WFEIS and $\Delta X = 25$ km for GFED. Since the spatial resolution of GFDD is 25 km, we conducted our evaluation at this spatial resolution. All three of the FEIS have temporal resolutions of 1 day and have been evaluated on time scales of $\Delta t = 30$, 10, 5, and 1 days. Because the fire regimes of the east and west are very different, an evaluation was carried out for the east and west separately, in addition to a CONUS wide evaluation. The figure of merit used to assess the FEIS across the different time scales is similar to that described in Urbanski et al. (2011). Briefly, for each time scale we calculated the element (k, t) total quantity of interest, X (X = BA, FC, ECO, EPM2.5) for each FEIS and the Reference Emission Inventory (REI) and the absolute error (e.g. AEFEIS = FCFEIS – FCREI). The elements (k, t) were arranged in order of increasing AE. The element wise cumulative distribution of X was plotted versus AE and the figure of merit as taken as the value of AE where the cumulative distribution of X breached 0.68. The FEIS figures of merit are plotted in Figure 5.

**Event Based Evaluation**

Daily burned area, fuel consumption, and emissions of the three FEIS were evaluated against the REI for twenty wildfire test cases in Table 2. These test cases were chosen because they were large, long duration fire events representative of the main wildfire regions of CONUS. The events were also selected for their spatial and temporal isolation from other fires which allowed for unambiguous attribution of the 25 km scale GFED emission to the specific fire events. Additionally, each event has multiple, consecutive airborne infrared (IR) mapped fire perimeters with IR flight logs which enabled an accuracy assessment of the daily burned area growth estimated by both the REI and the FEIS.

Table 2.

| Fire Name | Location | Vegetation Type | Final Size ($km^2$) |
|---|---|---|---|
| Bagley | Shasta-Trinity National Forest, CA | California Mixed Conifer forest | 189 |
| Cascade Creek | Gifford Pinchot NF, WA | Douglas-fir and spruce forest | 83 |
| Chips | Plumas NF, CA | California Mixed Conifer forest | 322 |
| Miller | Frenchglen, Oregon | Rangeland | 691 |
| Rush | Lassen County, CA on CA/NV border | Arid shrub/scrub with a minor (< 5%) conifer forest component | 1330 |
| Whitewater Baldy Complex | Gila NF, NM | Pinyon / juniper and ponderosa pine | 1204 |

**Economic Analysis**

The FEIS considered by the economics team included:

1. The Wildland Fire Emissions Information System (WFEIS) is funded by the National Aeronautics and Space Administration (NASA) Carbon Cycle Science and Applied Science Program and developed by the Michigan Tech Research Institute (French and Erickson, 2011). WFEIS helps resource managers' plan for prescribed and wildland fires by maintaining an online, interactive emissions calculator.

2. The Fire Emissions Tracking System (FETS) was developed to help Western Regional Air Partnership (WRAP) members manage smoke and plan for future fire seasons (Moore et al. 2007). In this effort, FETS makes fire data available in near-real time and stores past fire activity data. The Cooperative Institute for Research in the Atmosphere and Air Sciences, Inc. assists WRAP in development of the FEIS.

3. The 2008 National Wildland Fire Emissions Inventory (NEI) estimates wildland fire emissions for the U.S. Environmental Protection Agency's National Emissions Inventory (U.S. Environmental Protection Agency 2012; Raffuse et al. 2012). The NEI is specifically designed to

help implement the National Ambient Air Quality Standards (NAAQS). The U.S. Forest Service AirFire Research Team, which operates through the Pacific Northwest Research Station's Pacific Wildland Fire Science Laboratory, processes these estimations through the SmartFire2 and BlueSky frameworks.  Sonoma Technology, Inc. collaborates with USFS AirFire on the FEIS.

4. The Fire Inventory from NCAR (FINN) version 1 is a FEIS system designed to use any area burned dataset (Wiedinmyer et al. 2011).  (In the published report, estimates are given using MODIS data.)  Unique to FINN is its high-resolution estimation.  FINN is coordinated by the National Center for Atmospheric Research (NCAR), an organization operated by the University Corporation for Atmospheric Research (UCAR), which is funded by the National Science Foundation.

5. The Wildland Fire Emission Inventory (WFEI) is a product of the Missoula Fire Sciences Laboratory at the Rocky Mountain Research Station of the U.S. Forest Service (Urbanski et al. 2011).  WFEI was developed to support atmospheric chemistry studies that focus on the U.S., as well as aid in air quality forecasting.

6. The Wildfire Automated Biomass Burning Algorithm (WF_ABBA) is utilized to estimate emissions for the contiguous United States (Zhang et al. 2008).  The National Environmental Satellite, Data, and Information Services (NESDIS) aided the National Oceanic and Atmospheric Administration (NOAA) by developing WF_ABBA to estimate emissions in near real-time to assist operational air quality forecasts.

7. Global Fire Emissions Database version 3 (GFED3) estimates fire emissions for the globe (van der Werf et al. 2010). Developed by a coalition of university researchers, GFED3 evaluates fire emission fluctuations, and compares emission production from deforestation, savanna, forest, agricultural, and peat fires.

Of the seven FEISs under consideration, two evaluate global emissions and the remaining five evaluate emissions for some portion of the U.S. Except for WF_ABBA, all the FEISs that estimate U.S. emissions use CONSUME to model combustion.  GFED3 and FINN, which estimate global emissions, are not able to use this model as CONSUME is specific to the U.S. The data products used by the FEISs come primarily from MODIS and are almost always funded by the U.S. Forest Service, NOAA, or NASA.  Additionally, the link between FCCS and CONSUME implies that much of the distinction between the systems lies in the area burned input.

## Key Findings

### Economics Evaluation

The cost survey reveal the mean annual operating cost of the seven FEIS is $74,025 with standard deviation of $35,319. The cost survey respondents were asked to estimate annual operating costs if the FEIS were to remain operating in its current state without any major updates to its algorithm or data sources. It should be recognized that many of these systems are being updated with the latest advances in atmospheric chemistry, incorporating improved data inputs as these become available, and responding to improvements in computing technology and capabilities. While the economics team attempted to collect costs on all input data products, beyond the direct costs of the FEIS only CONSUME costs were included in the calculation of operating costs of the FEISs. After much consideration, the economics team determined that most of the other data inputs served many purposes and would exist independent of FEIS needs. Uniquely, the CONSUME model seems to have been developed primarily to serve the FEIS community. If CONSUME costs were not included in the FEIS costs, assuming their existence independent of the FEIS, the average FEIS annual operating cost would instead be $59,025. This latter statistic is more appropriate in the sense that the CONSUME model would have to be paid for just once to serve uses by multiple systems and the first statistics above included the full annual costs of CONSUME in each of the FEIS's that used it as an input. The prevalence of the CONSUME model, used by four of the seven FEIS, is indicative of an important, even if unsurprising, finding—many of the FEIS authors know each other, have working relationships, and collaborate to further the field.

**Burned Area, Fuel Consumption, and Emissions**

The annual CONUS burned area of all three FEIS plotted versus REI in Figure 6. All three FEIS are highly correlated with REI (r = 0.87, 0.94, and 0.95). WFEIS burned area is biased low for all years, while FiNN burned area is biased high. GFED burned area agrees well with REI for some years, but is biased low. In terms of fuel consumption, again all three FEIS are well correlated with REI (Figure 7). The fuel consumption bias of GFED and FiNN is consistent with the burned area bias, with MFB of -0.10 and 0.07, respectively. However WFEIS is in excellent agreement with REI (MFB = 0.01) despite the large difference in annual burned area, indicating a large difference in fuel loading. In fact, the fuel load consumed (kg dry biomass per $m^2$) is significantly lower for GFED and FiNN and higher for WFEIS (see Figure 8). Emitted PM2.5 is biased low for the FEIS (Figure 9) with MFB of -0.22, -0.05, -0.14 for GFED, FiNN, and WFEIS, respectively. The consistent difference in PM2.5 is indicative of the FEIS employing lower EFPM2.5 than assumed in REI.

The annual, CONUS wide comparison provides general insight into the performance of the FEIS. However, the FEIS must be examined at spatial and temporal scales relevant to air quality activities to obtain a useful assessment. In addition to our primary figure of merit (Figure 5), the FEIS were also evaluated at a spatial scale of 25 km and a time scale of 5 day. We used 5 day rather than 1 day as the accuracy of the burn day assignment of REI (or any of the FEIS) is uncertain and can only quantified using fire event level observations as discussed in subsequent sections. Table 3 shows the mean bias (MB) and mean error (ME) of the FEI variables for spatiotemporal elements of 25 km and 5 days.

Table 3. FEIS evaluation metrics for spatiotemporal elements of 25 km and 5 days

| Variable | metric | GFED | FiNN | WFEIS |
|---|---|---|---|---|
| Burned Area ($km^2$) | MB | -0.01 | 0.24 | -0.41 |
| | ME | 0.13 | 1.23 | 1.08 |

| | | | | |
|---|---|---|---|---|
| Fuel Consumed (Mg) | MB | -63.48 | 273.07 | 186.69 |
| | ME | 210.44 | 1886.68 | 2804.03 |
| Fuel Load Consumed (kg/m$^2$) | MB | -0.49 | -1.04 | 0.88 |
| | ME | 1.29 | 1.40 | 2.23 |
| CO Emitted (Mg-CO) | MB | -12.57 | -7.59 | -39.40 |
| | ME | 22.92 | 198.81 | 285.49 |
| PM2.5 Emitted (Mg-PM2.5) | MB | -2.16 | -5.13 | -14.78 |
| | ME | 3.53 | 28.02 | 40.32 |

$MB = \frac{1}{N}\sum_{i=1}^{N}(X_{FEIS} - X_{REI})$ ; $ME = \frac{1}{N}\sum_{i=1}^{N}|X_{FEIS} - X_{REI}|$

As can be seen from Table 3, the errors in burned area are quite small. Large differences begin to emerge in the fuel load consumed per unit area. This reflects a combination of both the pre-fire fuel loading and combustion completeness of the FEIS (B and $\alpha$ respectively in Eq. 1). Metrics for emitted CO and PM2.5 include additional differences in emission factors. Since emission factors are cover type specific differences in vegetation maps also play a role. The contribution of fuel loading, combustion completeness, and emission factors to differences among FEIS and with respect to the REI are best evaluated on a fire event basis as presented in the next section.

**Event Based Evaluation**

Six of the 20 fire events examined are highlighted to demonstrate keys findings of our FEIS evaluation. Figure 10 shows total event FEIS deviations from REI for burned area, fuel load, fuel load consumed, and emitted PM2.5.

1. Burned area based solely on MODIS active fire detections frequently underestimates actual burned area for fires occurring in rangelands, especially fires with rapid growth.
2. Burned area mapped with the MODIS MCD64 product tends to identify regions mapped as “unburned to low severity” in the LANDSAT based MTBS product as burned.
3. In forests there are large differences in fuel load consumed among the FEIS.
4. FiNN fuel load consumed is consistently biased low to REI for forest cover types
5. WFEIS fuel load consumed is consistently biased high to REI for forest cover types
6. GFED fuel load tends to be biased high to REI for forest cover types
7. Deviations of FEIS fuel load consumed from REI are often sufficient to outweigh differences in burned area.
8. WFEIS pre-fire surface fuel loadings are inconsistent with FIA data
9. There is significant uncertainty in EFs for western wildfires due to the lack of field observations. The REI employs EFs estimated assuming an MCE = 0.88, based on

limited field observations of western wildfires. The EFs used in FiNN and GFED are based on measurements from understory prescribed in the southeast US.

**Management Implications**

Overall fuel load consumed is greatest source of uncertainty in the emission inventories, particularly for forest fires. Improved mapping of fuel loading, especially for forest is needed to reduce the uncertainty of FEIS. The surface fuel loading for forests developed for the REI is based on over 28,000 FIA plots, and as such, provides the most rigorous modeling of surface fuel loading available. However, the REI simply uses a forest type map to assign per-fire fuel load. While this classification approach does have skill in assigning fuel loads (see Keane et al., 2013), a spatially explicit map based would undoubtedly provide more accurate and less uncertain assignment of forest fuel loads for modeling emissions. We recommend the An FIA plot data and plot locations differentiating forest type map distributions to burned pixels.

The economics team faced some resistance in survey completion by those in charge of the FEIS. Personnel with sufficient knowledge to answer the detailed survey are also those facing many demands. A few individuals indicated mild to strong opposition to the existence of a cost-effectiveness study of FEIS. Surveyed personnel expressed that each FEIS serves specific needs in the field that would go unfulfilled if that particular system did not exist. As such, suggestions were to conduct the cost-effectiveness analysis as an evaluation of complementary rather than competing systems. This coincides with our recommendation to consider all dimensions of FEIS in any future funding decision. Given that uncertainty measures were developed for three of the seven FEIS under consideration, the value of cost-effectiveness analysis is somewhat limited at this time. The manuscript summarizing this analysis is in final phases of completion

**Relationship to Other Recent Findings and Ongoing Work**

**Future Work Needed**

**Forest Fuel Loading**

We recommend the development of a spatially explicit forest fuels map based on FIA plot data. Specifically, a map developed from FIA plot data and plot locations and LANDFIRE spatial data layers (e.g. elevation, aspect, vegetation form and structure).

**Burned Area Dating**

Significant uncertainty remains in the assignment burn date to burned pixels in all available datasets, FEIS and REI. MODIS active fire detections are not frequent enough to robustly assign burning dates, especially for fires with rapid growth. In, theory MODIS MCD64 (and the upcoming VIIRS based sibling) could provide a more robust date assignment. Also, the GOES satellites which provide active fire detections with a frequency of 30 minutes should enable more accurate burn date assignment. However, the accuracy of burn date assignments by either the MODIS MCD64 or the GOES active fire detections have not been rigorously evaluated in peer-review study. We recommend a rigorous evaluation using incident fire perimeters be conducted to evaluate the accuracy of burn dates assigned by the MCD64 product and GOES active fire detections.  The accuracy of MCD64 burn dates will be addressed in study to be published as part of this project.

**Human Impacts**

Human impact on fire emissions are significant (e.g., Moeltner et al. 2013) and improving FEIS would enable public officials and the general public to make better decisions. Impact assessment of improved fire emissions data may be warranted to justify spending on development and operation of FEIS.

**Deliverables**

Deliverables, description and delivery dates

| Deliverable from Original Proposal | Delivered | Status |
|---|---|---|
| Refereed publications | Peer-reviewed articles<br>(1) Hansen et al. (2014) "Wildfire in hedonic property value studies."<br>(2) Hansen et al. (2016) "Forest-landscape structure mediates effects of a spruce bark beetle (Dendroctonus rufipennis) outbreak on subsequent likelihood of burning in Alaskan boreal forest."<br>(3) Keane, R.E., Herynk, J.M., Toney, C., Urbanski, S.P., Lutes, D.C., Ottmar, R.D. (2013) "Evaluating the performance and mapping of three fuel classification systems using Forest Inventory and Analysis surface fuel measurements."<br>A preliminary version of the reference forest fuel loading dataset developed in our project was evaluated in this publication along with two other fuel loading maps (LANDFIRE FCCS and FLM).<br>(4) Urbanski, S. (2014) "Wildland Fire Emissions, Carbon, and Climate: Emission Factors."<br>This publication is a synthesis of wildland fire emission factors developed for use in our project's reference emission dataset.<br>(5) Mallia, D. V., J. C. Lin, S. Urbanski, J. Ehleringer, and T. Nehrkorn (2015), "Impacts of upwind wildfire emissions on CO, CO2, and PM2.5 concentrations in Salt Lake City, Utah"<br>This study employed our project's reference emissions database. | Completed |
| FEIS evaluation peer-reviewed publication | Manuscript reporting the FEIS study for submission to Atmospheric Chemistry and Physics or Geoscientific Model Development | In preparation |
| Final report | A final report including the results for the objectives will be submitted to the JFSP. | This report serves as the final report |

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| Master's thesis | Research training for a post-baccalaureate student now second-year in a Ph.D. program in Economics. | Completed |
| Conference/symposia/ workshop | (1) Urbanski et al. "The contribution of fuel loading uncertainty to the variability among wildland fire smoke emission inventories", International Smoke Symposium, University of Maryland College Park, October 24, 2013.<br>(2) Urbanski et al. "Pollutant emissions from large wildfires in the western United States", Large Wildland Fires: Social, Political, and Ecological Effects, sponsored by the Association for Fire Ecology and the International Association of Wildland Fire, Missoula, Montana, May 21, 2014.<br>(3) Urbanski, et al. "Pollutant Emissions from Large Wildfires in the western United States", Community Modeling and Analysis System 14th Annual Conference, Chapel Hill, NC, October 5, 2015.<br>(4) Lin, et al. "Quantifying the Influence of Biomass Burning on Measurement Sites in the Western U.S.", American Geophysical Union Fall Meeting, San Francisco, CA, December 17, 2014.<br>(5) Mallia, et al. "Identifying and Quantifying the Impact of Wildfires on Utah's Air Quality", AMS Fire and Forest Meteorology conference, May 5-7th, 2015, Minneapolis, MN.<br>(6) Dr. Urbanski organized and moderated Special Session: "Wildland Fire Emission Factors – Latest research and implications for management and policy", International Association of Wildland Fire, Fire Behavior and Fuels Conference, Portland, OR, April 13, 2016.<br>(7) Urbanski, S. Emission Factors - Latest Research, International Association of Wildland Fire, Fire Behavior and Fuels Conference, Portland, OR, April 13, 2016. | Completed |
| | | |
| Presentation on cost-effectiveness of different FEIS. | Poster presentation "Fire Emissions Inventory Systems' Organization and Costs" 5th International Fire Behavior and Fuels Conference, April 2016. | Completed |

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|---|---|---|
| | Dr. Naughton presented "Frontiers in Fire Economics" Large Wildlands Fire Conference, May 2014. | |
| | Dr. Naughton co-organized a special session and co-authored two other presentations Large Wildlands Fire Conference, May 2014. | |
| Economics manuscript on cost-effectiveness of different FEIS | Manuscript "Organization, cost structure and cost-effectiveness of fire emissions inventory systems." | In preparation |
| Catalogue of FEIS | "An Organizational Study of Wildland Fire Emission Inventory Systems" | Completed |
| Dataset | The reference fire emissions inventory used I this project to evaluate GFED, FiNN, and WFEIS is being prepared for submission to the Forest Service Research Data Archive. | In preparation |

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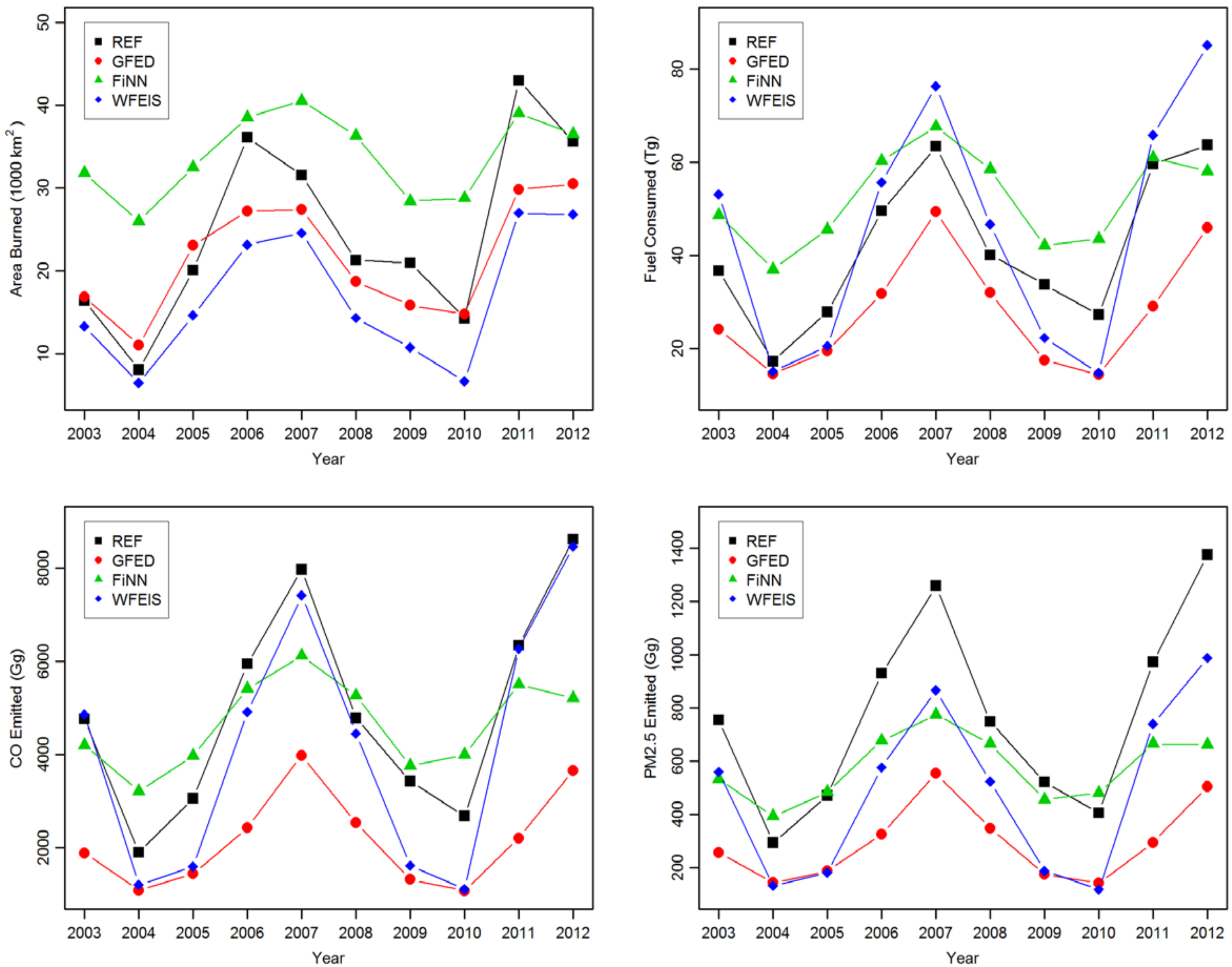
Figure 4.


REF
GFED
FiNN
WFEIS
Area Burned (1000 km$^2$)
Fuel Consumed (Tg)
CO Emitted (Gg)
PM2.5 Emitted (Gg)
Year
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012

# Figure 5.

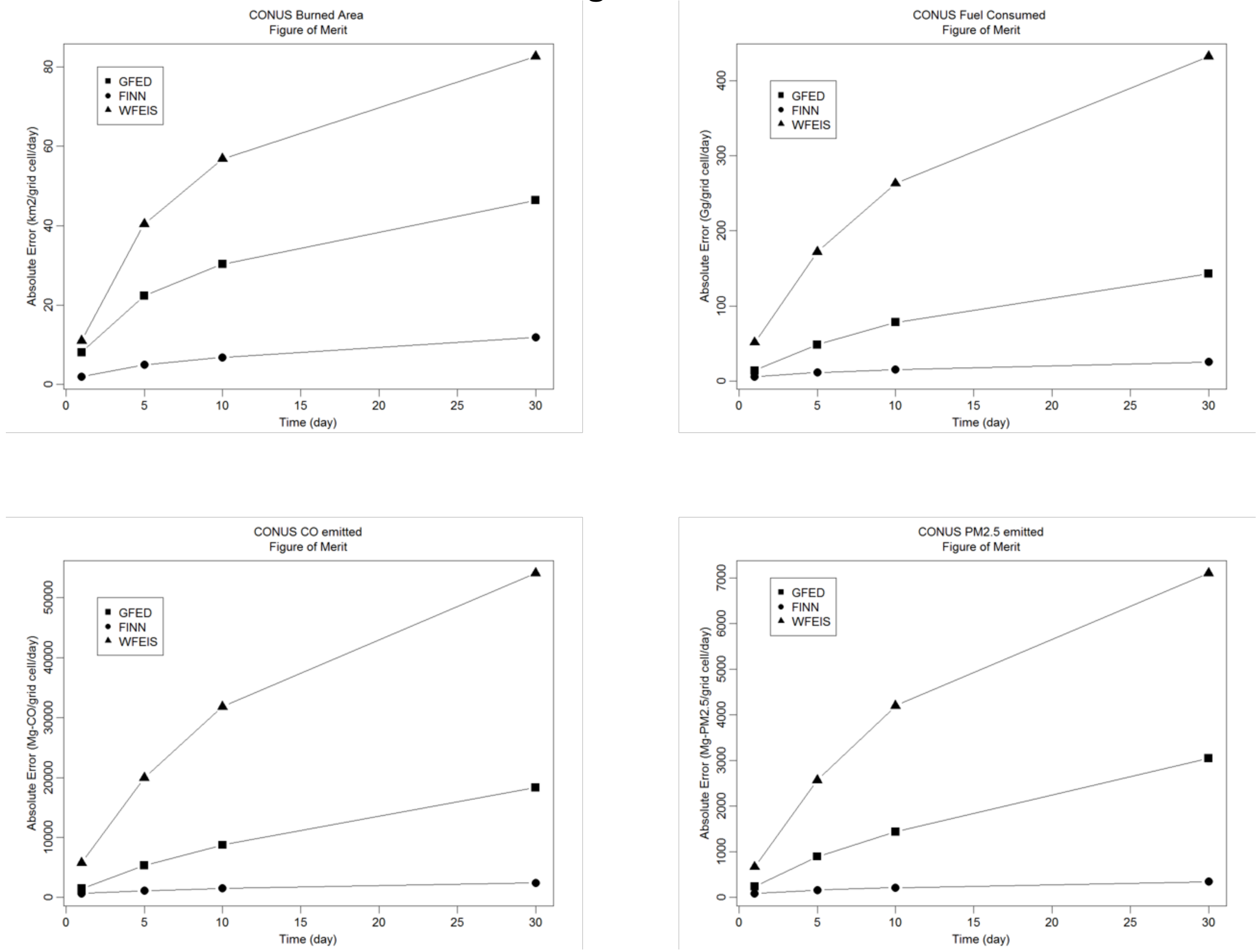
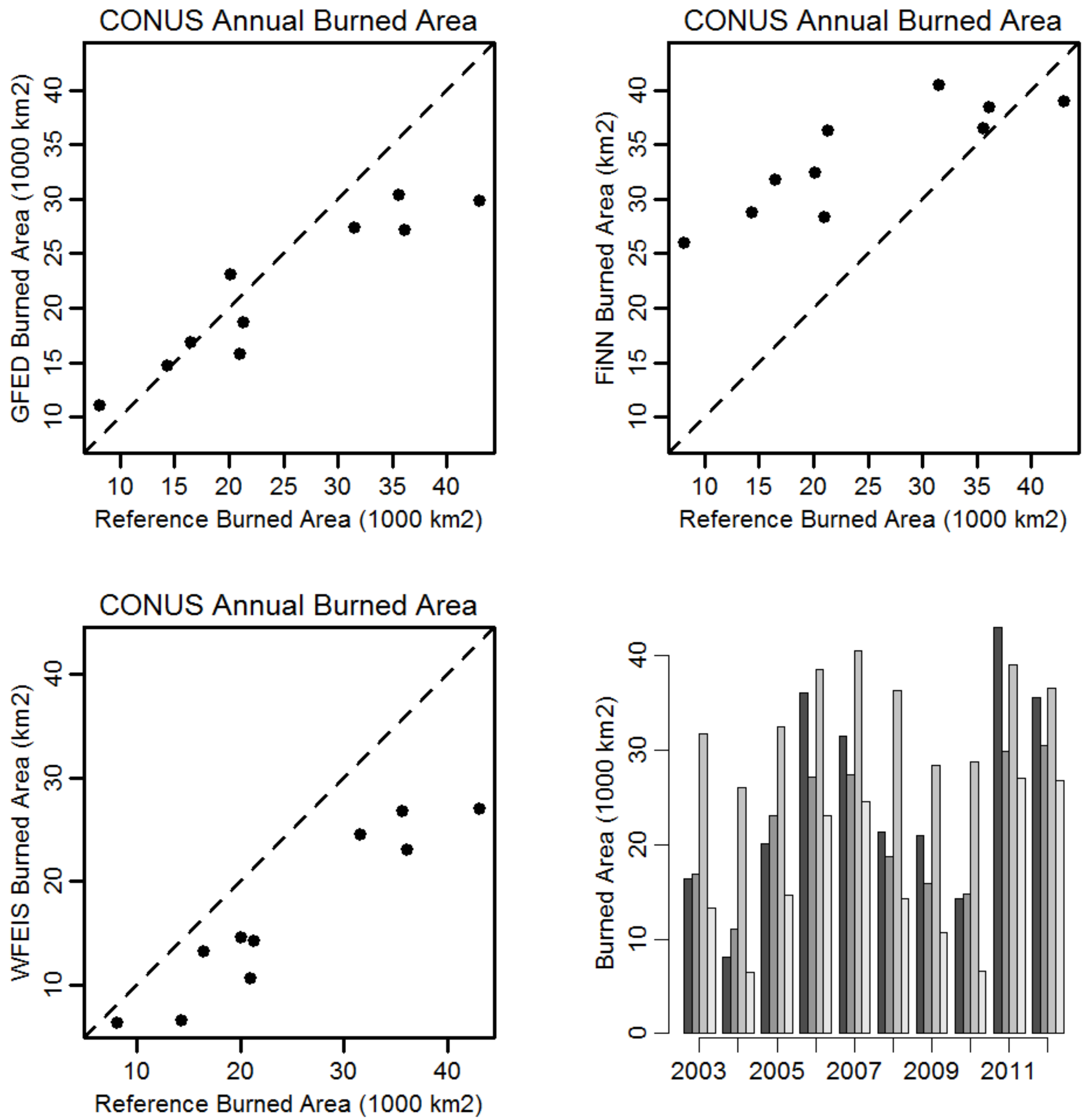
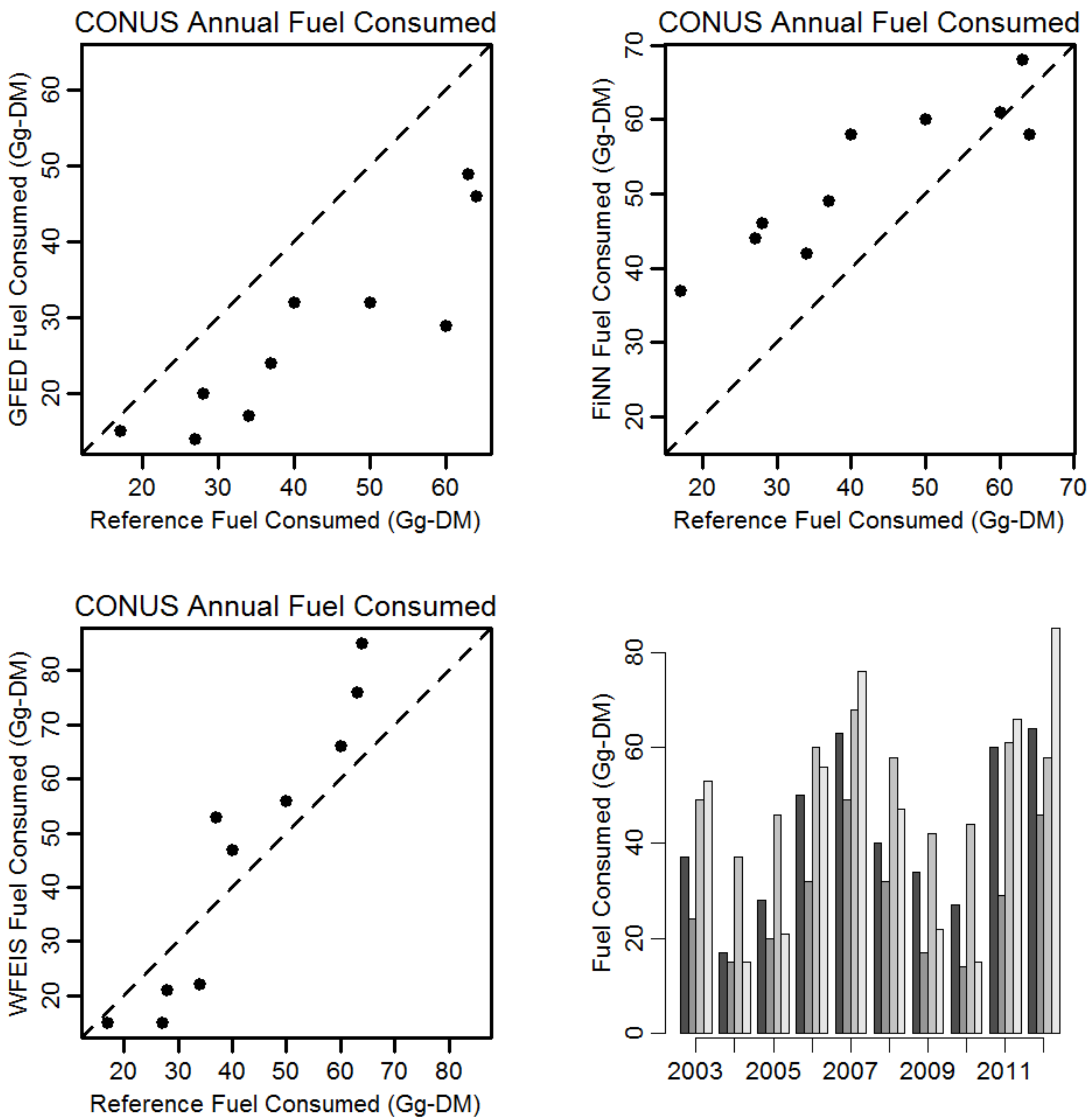

CONUS Burned Area
Figure of Merit
Absolute Error (km2/grid cell/day)
Time (day)
GFED
FINN
WFEIS
CONUS Fuel Consumed
Figure of Merit
Absolute Error (Gg/grid cell/day)
Time (day)
GFED
FINN
WFEIS
CONUS CO emitted
Figure of Merit
Absolute Error (Mg-CO/grid cell/day)
Time (day)
GFED
FINN
WFEIS
CONUS PM2.5 emitted
Figure of Merit
Absolute Error (Mg-PM2.5/grid cell/day)
Time (day)
GFED
FINN
WFEIS

Figure 6.



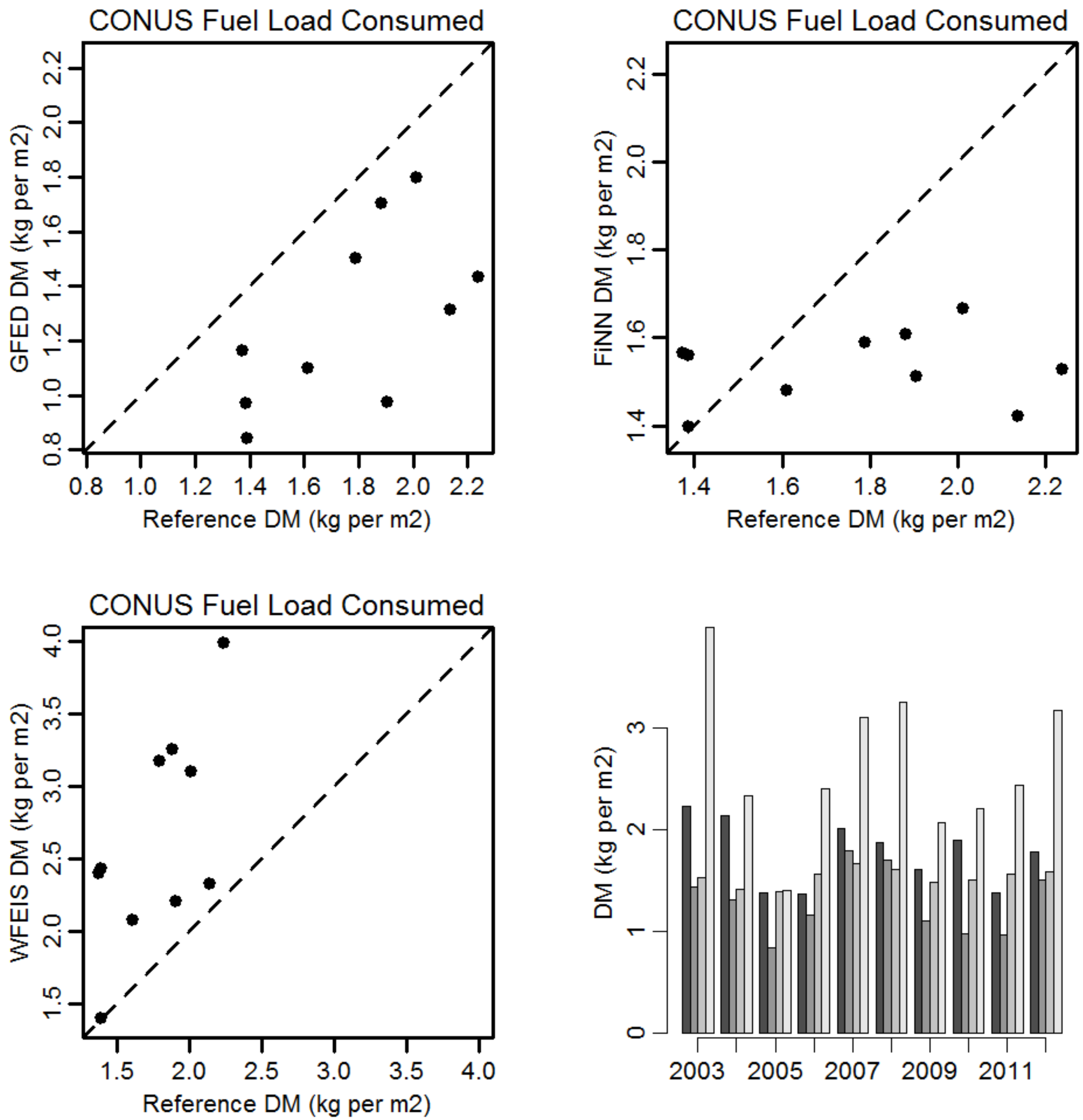
CONUS Annual Burned Area
GFED Burned Area (1000 km2)
Reference Burned Area (1000 km2)
CONUS Annual Burned Area
FiNN Burned Area (km2)
Reference Burned Area (1000 km2)
CONUS Annual Burned Area
WFEIS Burned Area (km2)
Reference Burned Area (1000 km2)
Burned Area (1000 km2)
2003
2005
2007
2009
2011

Figure 7.



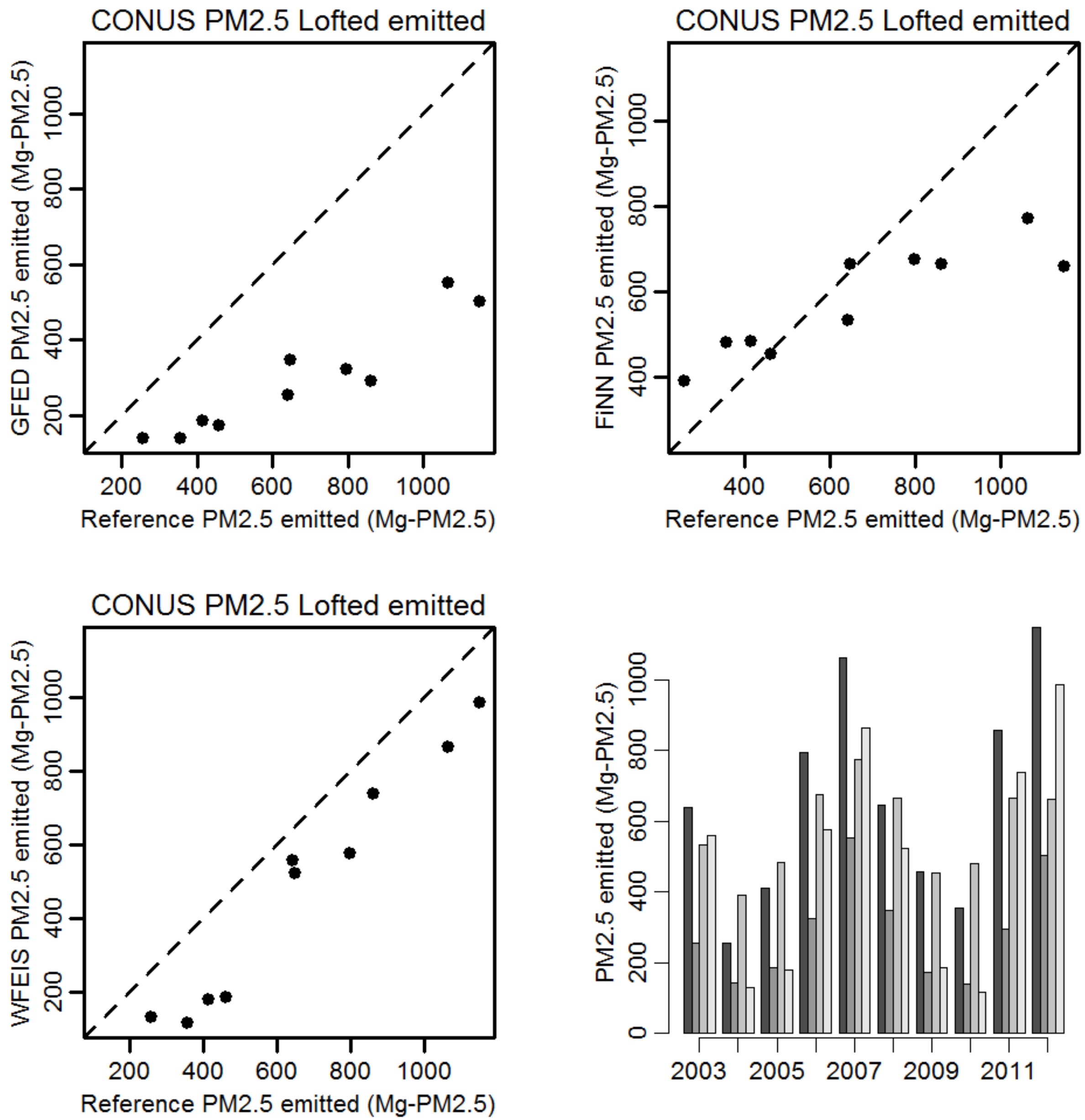
CONUS Annual Fuel Consumed
GFED Fuel Consumed (Gg-DM)
Reference Fuel Consumed (Gg-DM)
CONUS Annual Fuel Consumed
FiNN Fuel Consumed (Gg-DM)
Reference Fuel Consumed (Gg-DM)
CONUS Annual Fuel Consumed
WFEIS Fuel Consumed (Gg-DM)
Reference Fuel Consumed (Gg-DM)
Fuel Consumed (Gg-DM)
2003
2005
2007
2009
2011

# Figure 8.



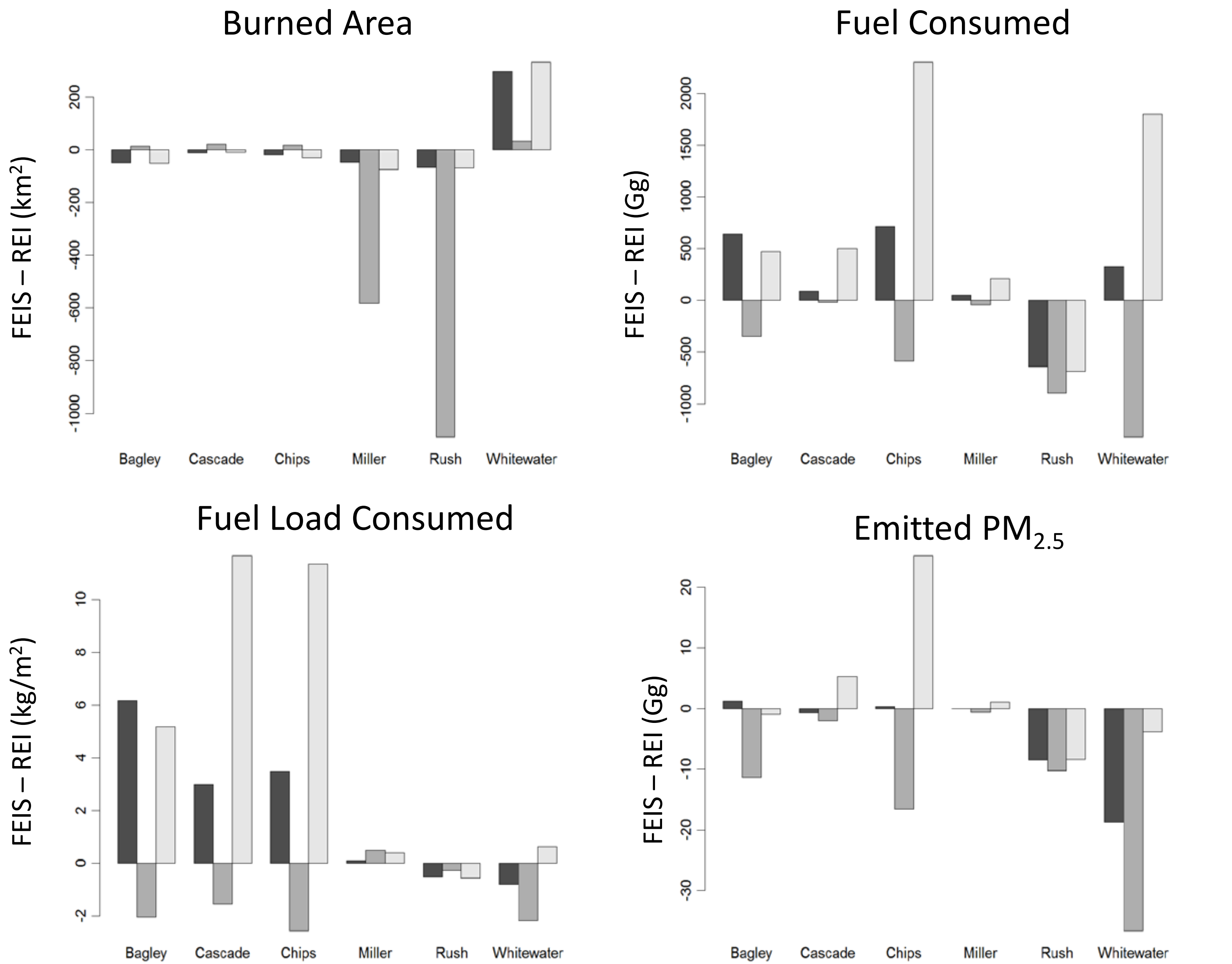
CONUS Fuel Load Consumed
GFED DM (kg per m2)
Reference DM (kg per m2)
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
CONUS Fuel Load Consumed
FINN DM (kg per m2)
Reference DM (kg per m2)
1.4
1.6
1.8
2.0
2.2
CONUS Fuel Load Consumed
WFEIS DM (kg per m2)
Reference DM (kg per m2)
1.5
2.0
2.5
3.0
3.5
4.0
DM (kg per m2)
0
1
2
3
2003
2005
2007
2009
2011

Figure 9.



CONUS PM2.5 Lofted emitted
GFED PM2.5 emitted (Mg-PM2.5)
Reference PM2.5 emitted (Mg-PM2.5)
CONUS PM2.5 Lofted emitted
FINN PM2.5 emitted (Mg-PM2.5)
Reference PM2.5 emitted (Mg-PM2.5)
CONUS PM2.5 Lofted emitted
WFEIS PM2.5 emitted (Mg-PM2.5)
Reference PM2.5 emitted (Mg-PM2.5)
PM2.5 emitted (Mg-PM2.5)
2003
2005
2007
2009
2011

Figure 10.


Burned Area
FEIS – REI (km$^2$)
200
0
-200
-400
-600
-800
-1000
Bagley
Cascade
Chips
Miller
Rush
Whitewater
Fuel Consumed
FEIS – REI (Gg)
2000
1500
1000
500
0
-500
-1000
Bagley
Cascade
Chips
Miller
Rush
Whitewater
Fuel Load Consumed
FEIS – REI (kg/m$^2$)
10
8
6
4
2
0
-2
Bagley
Cascade
Chips
Miller
Rush
Whitewater
Emitted $PM_{2.5}$
FEIS – REI (Gg)
20
10
0
-10
-20
-30
Bagley
Cascade
Chips
Miller
Rush
Whitewater