Validation of Fuel Consumption Models for Smoke Management Planning in the Eastern Regions of the United States

Final Report to the Joint Fire Science Program

JFSP Project Number: 08-1-6-01

Project Website: http://www.fs.fed.us/pnw/fera/research/smoke/consumevalidation.shtml

Date: December 31, 2011

Principal Investigator: Roger Ottmar, Research Forester, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, 400 North 34th Street, Suite 201, Seattle, WA 98103.; Phone: 206-732-7826; e-mail: rottmar@fs.fed.us

Co-Principal Investigator: Matthew B. Dickinson, Northern Research Station, 359 Main Road, Delaware, OH 43015; Phone: 740-368-0096; e-mail: mbdickinson@fs.fed.us

Co-Principal Investigator: Elizabeth Reinhardt, US Forest Service, 201 14th St. Southwest, Washington DC 20250; Phone: 202-205-8513; e-mail: ereinhardt@fs.fed.us

This research was sponsored in part by the Joint Fire Science program. For further information go to www.firescience.gov

TABLE OF CONTENTS

I. ABSTRACT

Fuel consumption is a critical component for estimating the effectiveness of prescribed fire for reducing fuels, emissions, and other fire effects. Because little research on wildland fuel consumption has been conducted in the eastern United States, there are few reliable validation datasets to assess the sensitivity, biases, and uncertainties of currently used fuel consumption models. We measured fuel loading and fuel consumption on 18 prescribed fires in southern pine forest and sand pine scrub fuelbed types in the Southeastern United States, and in 11 mixed hardwoods and pitch pine fuelbed types in Northeast and North Central states. The data from the 29 units have been compiled and placed in the SEMIP repository as a data set that can be used to evaluate fuel consumption and other fire models. Additionally, pre-fire and post fire fuel consumption data from other studies occurring in the eastern and western United States was compiled and added to it more usable as a validation data set.

The data collected from the 29 units were used to test Consume and the First Order Fire Effects Models (FOFEM), two currently available fuel consumption prediction systems. The study suggests that, with the exception of fine woody fuels, there are no discernible differences between model results (how they predicted consumption) on the 18 pine sites and 11 mixed hardwood sites. Overall, both systems perform well in predicting shrub and herbaceous consumption, but did a poor job in predicting 1-hr, 10-hr, litter, and duff fuel consumption. More work is needed to develop reliable models of small woody fuels, litter, and duff consumption for the eastern fuel types.

Airborne infrared mapping and associated ground measurements were performed with the Wildfire Airborne Sensor Platform (WASP) on eight fires for this project. Two fires were monitored in both Ohio (Tar Hollow State Forest) and Kentucky (Mammoth Cave National Park). An additional four units were monitored in Florida (Eglin Air Force Base). Ground measurements (N = 19) consisted of nadir-viewing, dual-band radiometer measurements of total ground-leaving fire power and fire video. Airborne and ground data from this project are combined with data from other projects to provide >20 airborne datasets and >60 ground measurement points. A new calibration approach allows us to use data from a single bandpass infrared detector to estimate total fire power. This calibration method provides a check and alternative to ground calibration of airborne fire mapping data and is expected to be widely applicable. With the new calibration, we will map fire heat release and fuel consumption for comparison with Consume and FOFEM.

II. BACKGROUND AND PURPOSE

Fuel consumption is the amount of biomass consumed during a fire, a critical component for estimating the amount and source strength of emissions, the effectiveness of prescribed fire for reducing fuels, the rate of heat generated, and numerous fire effects such as soil heating and potential tree mortality. This is especially critical in the eastern United States where prescribed burning is a key fuels reduction and restoration technique (Wade and Lunsford 1989, Marshall et al. 2008) and where expansion and development of the wildland-urban interface require accurate smoke production estimates from prescribed burns to comply with EPA emission regulations and to protect public health, particularly in areas with high population density (Theobald and Romme 2007, Zhang et al. 2008).

Although fuel consumption can be measured in the field, the cost is often prohibitive. To reduce this cost and provide a reliable means for estimating fuel consumption, Consume and FOFEM were developed by Forest Service Research to provide fuel consumption prediction. However, these models have not been adequately validated. Consume (Prichard et al. 2007, JFSP 2009) is a software application that estimates fuel consumption for wildland fires. It contains empirically derived fuel consumption equations specific to fuel category (e.g., shrubs, herbaceous vegetation, litter, duff, and woody fuels by time lag class) that represent the western, southeastern, and boreal forest regions of the United States. It also contains physically-based equations with empirically-derived constants to predict fuel consumption in recent logging slash. FOFEM (Reinhardt et al. 1997, Reinhardt 2003) estimates fuel consumption for different regions of the country by fuelbed category using the BURNUP model (Albini, 1994, Albini and Reinhardt 1995, Albini et al. 1995, Albini and Reinhardt, 1997). Burn-up is a mechanistic woody fuel consumption model (Lutes, in review).

Because little research on wildland fuel consumption has been conducted in the East, there are few reliable validation dataset to assess the sensitivity, biases, and uncertainties of fuel consumption models currently housed within Consume and FOFEM. The objective of this study was to collect a fuel consumption dataset, including pre- and post-burn fuel characteristics and day-of-burn environmental variables, to (1) help determine each models uncertainties, biases, or application limits in the East, and (2) contribute predictive models of fuel consumption in eastern forests. A total of 29 burn units were burned and monitored for fuel consumption between December and April 2009 and 2010 as part of this study.

This research focused on five related objectives to improve fuel consumption and thus smoke management capabilities in the eastern United States:

1. **Collect a set of pre-fire fuel characteristics, fuel consumption, and environmental input data for developing a fuel consumption validation set**
2. **Determine the uncertainties, biases, and application limits of applying Consume 3.0 to wildland fires for two fuelbed types found in the eastern regions of the United States**
3. **Determine Consume and FOFEM fuel consumption predictive uncertainties, biases or application limits in the eastern United States**
4. **Modify Consume 3.0 as needed and conduct a regional fuels workshop**
5. **Provide data sets for prescribed-fire-scale mapping of fire heat release and fuel consumption**

III. STUDY DESCRIPTION AND LOCATION

The primary goal of this study was to measure fuel consumption during prescribed burn operations in southern pine forest and pine scrub fuelbed types in the southeastern United States and mixed hardwoods and pitch pine fuelbed types in the northeastern and north central United States. The data was used to create a validation data set and to test current fuel consumption models. Burn-unit scale estimates of fuel consumption from airborn fire mapping will be used to determine how well coarse-spatial-scale estimates of fuel consumption represent variability on the landscape.

Study Sites

Local and regional federal and state fuels managers and air quality regulatory agency personnel were identified (e.g. Jeffrey Lewis, Daniel Boone National Forest, John Ashcraft, Mammoth National Park, Gary Cursio, North Carolina department of Forest resources, Kevin Hiers, Jackson Guard, Florida, Jim Brenner, Florida Forest service, John Blake, Savannah River Site and others) and questioned followed by a literature review to determine the most important fuelbed types to monitor for this fuel consumption validation project. Through this investigation, we targeted mixed hardwood in the northeastern and north central and central United States and southern pine and sand pine scrub fuelbeds in the southeastern United States (fig. 1) (Appendix 1). A total of 11 mixed hardwood units were burned in Kentucky, Virginia, and Ohio. Sites varied from containing developed understories to little or no understory species. A total of 15 southern pine forests were burned in Florida and South Carolina and are dominated by longleaf and loblolly pine with saw palmetto and gallberry understories. Most of the sites in the southeastern United States are burned about every 3 years. The remaining 3 burn units are pond pine/sand live oak sites in Pumpkin Hill State Reserve, Florida and had not burned in over 20 years. The units selected occurred across a range of fuel loadings and burned at a variety of fuel moisture and weather conditions within the range of prescribed burn planning requirements. Heat release from a total of eight prescribed fires in Ohio (N=2), Kentucky (N=2), and Florida (N=4) was mapped using the Wildfire Airborne Sensor Package (WASP). Because of aircraft mechanical problems and marginal weather, we were unable to fly additional fires on the Daniel Boone National Forest in Kentucky and on the George Washington-Jefferson National Forests in Virginia.

Fuel Loading, Fuel Consumption, and Fuel Moisture Field Measurements

Twenty-two plots were systematically located in a one-chain (66 ft) grid in each of the units. Plot centers were marked with steel conduit, flagging, and sequentially numbered steel tags. One portable meteorological station was established on several units before burning to monitor weather and fuel moisture variables. Consumption of shrubs, grasses and herbs, down dead woody fuels, litter, and duff were quantified using standard techniques (figs. 2 and 3).

At each plot, three 66-ft long planar intercept transects (Brown 1974) were established for the pre-burn and the post-burn woody fuel inventories (fig. 3). The first azimuth was randomly chosen and rounded to the nearest 10° for the pre-burn inventory with the remaining azimuths 120° and 240° from pre1 for each set of three azimuths. The post-burn azimuths were offset 60°

from the pre-burn (pre) azimuths (e.g., if pre1 = 0°, pre2 = 120° and pre3 = 240° then post1 = 60°, post2 = 180° and post3 = 300°). Logger's tapes were unreeled from the plot center and left out while the inventory is performed. Along each line, 10-hour fuels were tallied within 10 feet of the endpoint, progressing towards the plot center (i.e., from 33 to 23 feet on the tape). One-hundred-hour timelag fuels were counted along the entire 33-foot transect. The diameter at the point of intersection, species and decay status of 1000-hour fuels were measured along the entire 33-foot transect as well. Because we were running different azimuths in the pre- and post-burn inventories, we spent extra time and effort to ensure a complete count of all 10- and 100-hour fuels that may be buried in the surface material.

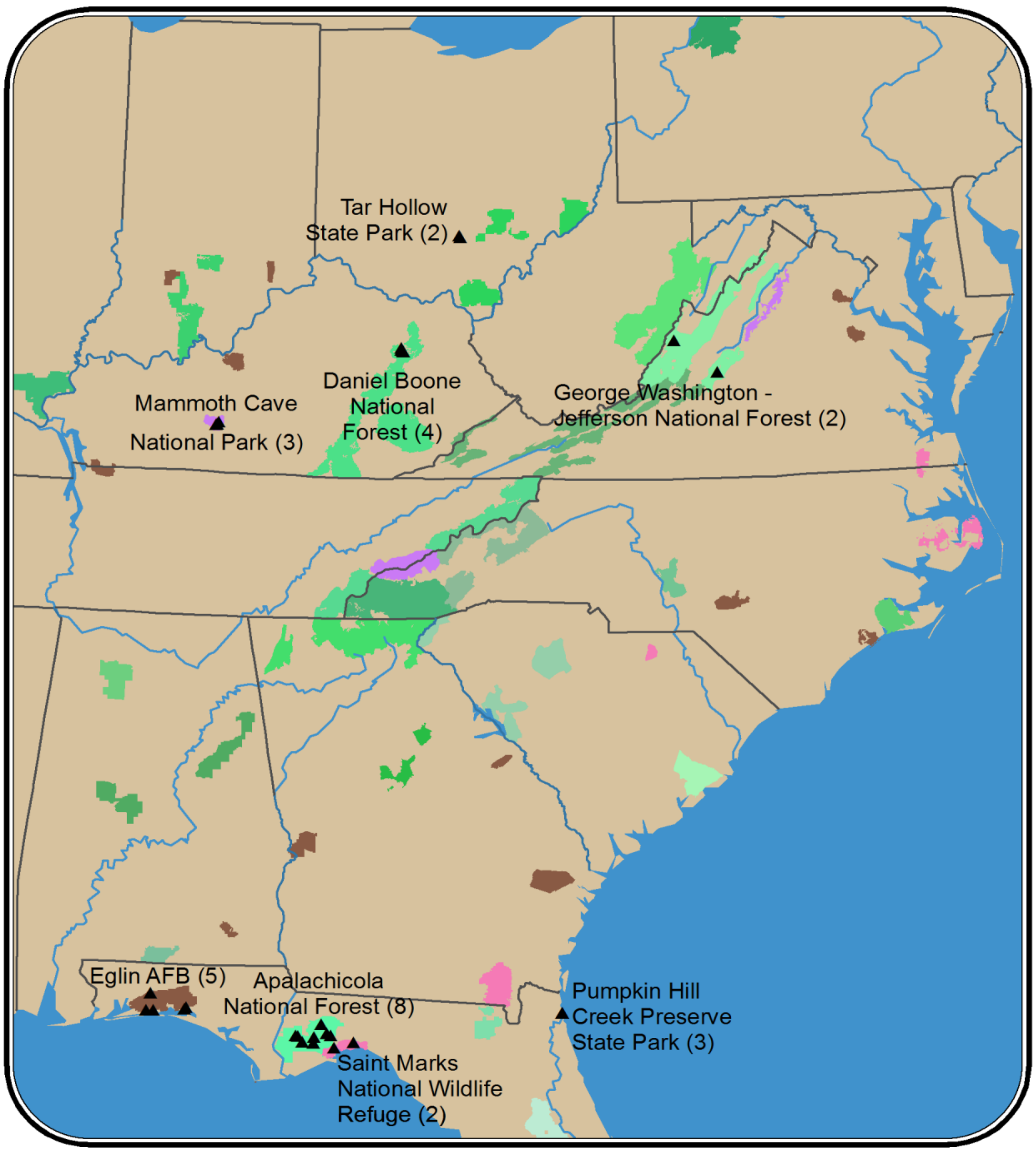


Figure 1. Location of fuel consumption study sites.

Figure 2. Establishing plots and measuring pre-fire and post-fire fuel loads.

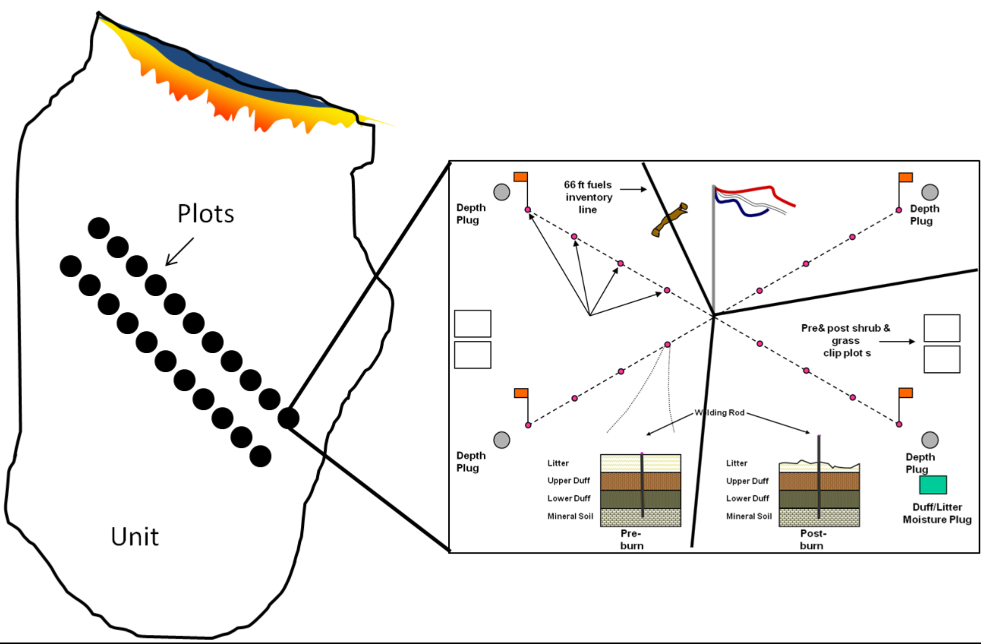


Figure 3. Fuel consumption plot layout.

Percentage cover of shrubs by species was be sampled on every odd set of woody lines (i.e., three 66-ft lines on 15 plots). Percentage black was determined on post woody lines in the same manner. Large woody fuel consumption (>3 inch diameter) was measured on units containing logs by wiring 20 logs in each unit and measuring diameter reduction after the burn. Each wired log was flagged, recorded by tag number and referenced by distance and azimuth from the nearest plot center. Logs were >3 inches in diameter and at least 10 feet in length. Wires were placed at the log's midpoint. An equal representation of decay classes and sizes was sampled in each unit.

Sixteen duff pins were placed at each plot according to plots (Beaufait et al. 1977). Pins were placed .5, 1, 1.5, and 2 meters from the plot center in each of the four cardinal directions. Wire flags marked the locations of the pins that are placed two meters from the plot center.

Depth of the surface material was measured to the nearest millimeter. Surface material was current year and 1-2 year old needles and leaves that have not yet started to break down and decay structurally (i.e., whole needles or leaves that may or may not be discolored). Surface material types were designated for each pin and recorded as the following:

Two photographs were taken at each plot. A logger's tape was laid out 30 feet due north from the plot center. The first photo was taken horizontally from the plot center looking north. A second photo of the plot and the pins was taken horizontally from 10-15 feet north of the plot.

Before each burn, fuel loads and other characteristics were collected using standard destructive methods in gridded subplots. All standing vegetation rooted within the boundaries of each subplot was cut at ground level, separated by species and status (live and dead), dried in an oven, and weighed. Surface fuels (litter, duff and small woody fuels) were collected in small subplots (0.25 m^2) nested within the standing vegetation subplots, dried in an oven, and weighed. Where present, large woody fuels were estimated using a planar intersect inventory (Brown 1974).

Fuel moisture samples and weather variables were collected immediately before each prescribed fire. Three to ten fuel moisture samples were collected representing the unit's dominant litter and duff material types. Moisture samples were also collected for the grass, shrub, 1-; 10-; 100-; and 1000-hour time-lag woody fuels. Wet weights were measured within 24 hours of sampling and samples were dried for 48 hours at a minimum of 158º F and reweighed. As various burn units came into prescription, a field crew was dispatched to set-up fire weather monitoring equipment adjacent to the burn unit and to collect live and dead fuel moisture samples on the day of the burn. Field personnel assisted with the burning operation as needed, and made observations of in-unit weather as the study areas burn. Once burning operations were completed, the crew remained to perform post-burn fuel sampling following pre-burn sampling protocols.

<u>Airborne IR imaging and ground-based calibration</u>

Airborne IR imagery was collected with the WASP instrument (see below) over entire burn units. The procedure was to have the aircraft deployed on a manned, fixed-wing aircraft and to fly at a sufficient altitude (5,000 – 10,000 ft above ground level) to image most or all of a given burn unit with a single image. The aircraft made passes as quickly over the fire as possible from the beginning of ignition operations through the end of the main combustion period. The airborne IR flight was coordinated with ground-based and helicopter ignition so that the main flaming phase and the bulk of the residual consumption process was sampled in its entirety over the target area. Three to four in-scene fiducials (small, hot targets, such as hibachis) were used as ground control points during the burns to improve the airborne registration accuracy during image orthogeorectification.

Accurately estimating ground-leaving IR heat release with the WASP instrument requires a calibration method. We have developed a first-principles calibration method (Appendix 5) as a part of this project and also conducted ground calibration. Ground calibration consists of nadir-viewing ground-based IR sensors within the target area (Fig. 4). The ground-based sensors were calibrated in the laboratory to provide an absolute measure of radiant heat flux (fire radiative power, FRP, kW/m^2) from long-wave IR data. The ground sensors detect IR radiation in the same wavelength band as the airborne WASP camera. Ground calibration not only was used to calibrate WASP but also to correct for atmospheric transmission (e.g. effects of smoke and haze). Ground-based IR sensors (N=6) were mounted on 6.1m 'data towers' that were erected near a set of fuel consumption plots. The ground-based sensors and WASP-acquired data simultaneously (both were synchronized to the GPS clock) and towers were located by using a survey grade GPS so that ground and airborne measurements are spatially coincident. Details on how FRP data are used to estimate total and rate of fuel consumption and fire rate of spread were provided in Data Analysis, below.

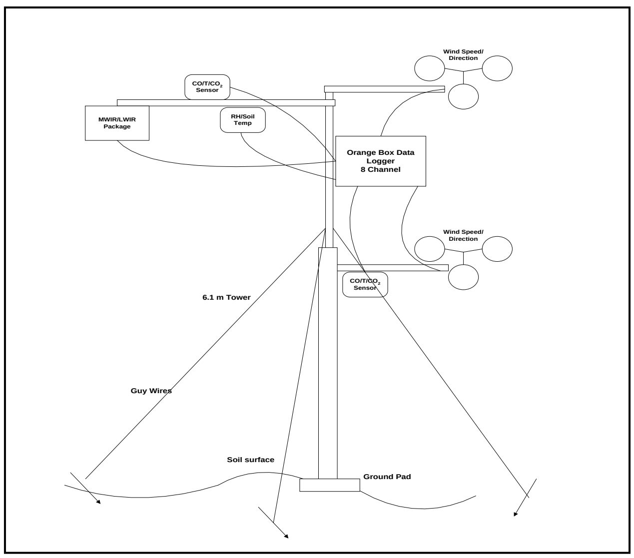


Figure 4. The data towers used to calibrate the overhead imagery to radiant heat release and thus, fuel consumed.

Ground-based weather, fire behavior, IR and gas sensing

The 20 ft 'data towers' contained dual band infrared sensors weather sensors (wind speed, direction and air temperature and RH) and gas (CO and CO_2) sensors at two heights. General weather information was monitored adjacent to the fire. Protracted smoldering combustion of large-diameter woody material were not well characterized because the combustion was often shielded from view and occurs over a time period that is very short compared with the flight duration of the fixed wing aircraft. Carbon monoxide and CO_2 sensors were deployed to provide independent estimates of the time course of both fuel consumption and combustion efficiency and, thus, the importance of flaming *versus* smoldering combustion. General fire behavior was characterized by in-fire video. Fire hardened video recorders with extended memory (~ 5 hours of imaging) were placed so as to view the fuel consumption plots and towers.

Data Analysis

Measurements of fuel loading, fuel depth, fuel consumption, fuel moisture content, percentage black, temperature, relative humidity, and wind speed were reduced to a "unit average" for each of the 29 study sites. This data was entered into summary tables (Appendix 1), Microsoft Excel spreadsheets (Appendix 2), and a Microsoft Access database (Appendix 3) as a validation data set. The database also contains other data sets from the eastern and western United States. However, no data reduction or analysis was performed on these data sets. Appendix 4 contains the list of data sets from the airborne flights.

We parameterized Consume v 4.1 and FOFEM v 5.9 with the average preburn data from each unit. Inputs in common to both models include: herbaceous, shrub, 1-hour, 10-hour, 100-hour, and 1000-hour fuel loads and 10-hour, 1000-hour and duff fuel moisture content. Additional Consume v 4.1 inputs include percentage live (i.e., the percentage of living biomass) for shrub and herbaceous fuel components, an estimate of "percent black" for the shrub stratum (i.e., the percentage of the shrub stratum blackened by the prescribed burn), litter depth, percentage cover of litter, litter arrangement (normal), duff depth, duff derivation (upper), and duff percentage cover. Additional FOFEM inputs include forest cover type (SAF 70, 3-yr rough), season of burn (winter/spring), duff depth, duff load, litter load, and percentage of rotten logs. Default FOFEM settings include region (Southeast), fire type (moderate), and consumption (natural-fuel). In four units (GWJ_JR, GWJ_CM, MBGH, A34), the measured duff load or moisture content was out of the range of FOFEM hard limits, so the nearest acceptable value was used.

Consume and FOFEM were used to predict consumption of the 8 fuel components: herbaceous, shrub, 1-hour, 10-hour, 100-hour, 1000-hour sound, 1000-hour rotten, litter, and duff. For each fuelbed category we plotted predicted consumption versus measured consumption. To assess model performance, we conducted a model equivalence test, which tests against the hypothesis that models are dissimilar (Robinson and Froese 2004, Robinson et al. 2005).

Airborne IR data will be used to generate landscape-scale estimates of fuel consumption and its' error. Landscape estimates will be compared with estimates derived from fuel consumption plots and Consume 4.1. Calibration of the airborne imagery will be conducted as described in Appendix 5 and compared with ground-calibration data from the data towers. Ground-based estimates of consumption at each fuel consumption plot will serve as a check on the accuracy of estimates derived from airborne imagery. Fuel characteristics from the dataset were used to build fuelbeds in the Fuel Characteristic Classification System (Ottmar et al. 2007) which fed the information by fuelbed category into Consume 4.1. Using fuel moisture and environmental variables from the validation set, fuel consumption estimates were made. These estimates were compared to the measured consumption values from the validation set.

We obtained the fire radiated flux density (FRFD, kW/m^2) from in-scene calibration of the overhead imagery using the 'data towers'. The data towers contain dual band infrared sensors (MWIR, LWIR) that provide an absolute measure of both the emissivity- area product and radiant temperature. This technique is not new, and is generally referred to as 'two-color thermometry'. The FRFD can be derived from these two quantities, without further assumptions (see Kremens et al. 2010). This data were then correlated with overhead data to get an airborne, landscape scale measure of FRP. We integrated (over time) the FRP measurements obtained in this fashion to obtain the fire radiated energy density (FRED, kJ/m^2)), which is proportional to the fuel consumed (Kremens et al. 2011), and thus smoke and particulates released. In previous experiments we measured mid-spatial-scale ($16m^2$) FRFD and FRED and correlated this to fuel consumed in eastern hardwood fuel types with great success (Kremens et al. 2011). We will extend the analysis described in Kremens et al. (2011) to the ground datasets collected in this and other projects (e.g., Rx-CADRE).

Currently, methods described in Ononye et al. 2007 are being automated and applied to the WASP datasets in order to identify firelines for estimates of integrated heat release and fuel consumption. Other automated techniques for describing burn-unit-scale heat and smoke release through the lifetime of fires are also being programmed. With our calibration method (Appendix 5) and automated image analysis techniques, we will be able to proceed with burn-unit-scale fire heat release and fuel consumption predictions that will be compared with Consume and FOFEM.
.

IV. KEY FINDINGS (RESULTS AND DISCUSSION)

The findings for the 29 units measured for fuel consumption and Consume and FOFEM evaluations are presented in the environmental dataset, fuel loading, and fuel consumption tables (Appendix 1), spreadsheet (Appendix 2), database (Appendix 3), and the draft manuscript (Appendix 6). The airborne datasets are listed in Appendix 4 and discussion of research is provided in a draft manuscript (Appendix 5). A simple summary and discussion is presented here.

A. Collected Fuel Load and Fuel Consumption Validation Dataset for Units in the Eastern United States.

Pine units in this study were frequently burned with generally low pre-fire fuel loading measured for the shrubs, herbaceous, litter, duff, and woody fuelbed categories, and ranged from 2.1 tons/ac to 9.3 tons/ac (fig. 5) (Appendix 1). In all cases, duff was nonexistent. Mixed hardwood units had a longer period between fires, loadings were substantially higher than in the pine units, and preburn fuel loadings ranged from 10.3 tons/ac to 34.6 tons/ac. In the pine sites, total fuel consumption ranged from 0.7 tons/ac to 5.3 tons/ac (fig. 6). Although more fuel consumption was measured on the mixed hardwood sites, it was limited and ranged from 2.2 to 6.7tons/ac.

Although no study sites had a heavy fuel load or were burned under extreme fire conditions, pre-fire loading and fuel consumption were typical of most sites being burned today in the East (Ottmar and Vihnanek 2000, Ottmar et al. 2003, Wright and Eagle 2011, JFSP 04-4-1-02) (Appendices 1 and 2). This will provide a typical validation data set for use to evaluate or modify future fuel consumption models to better represent prescribed burning in the East.

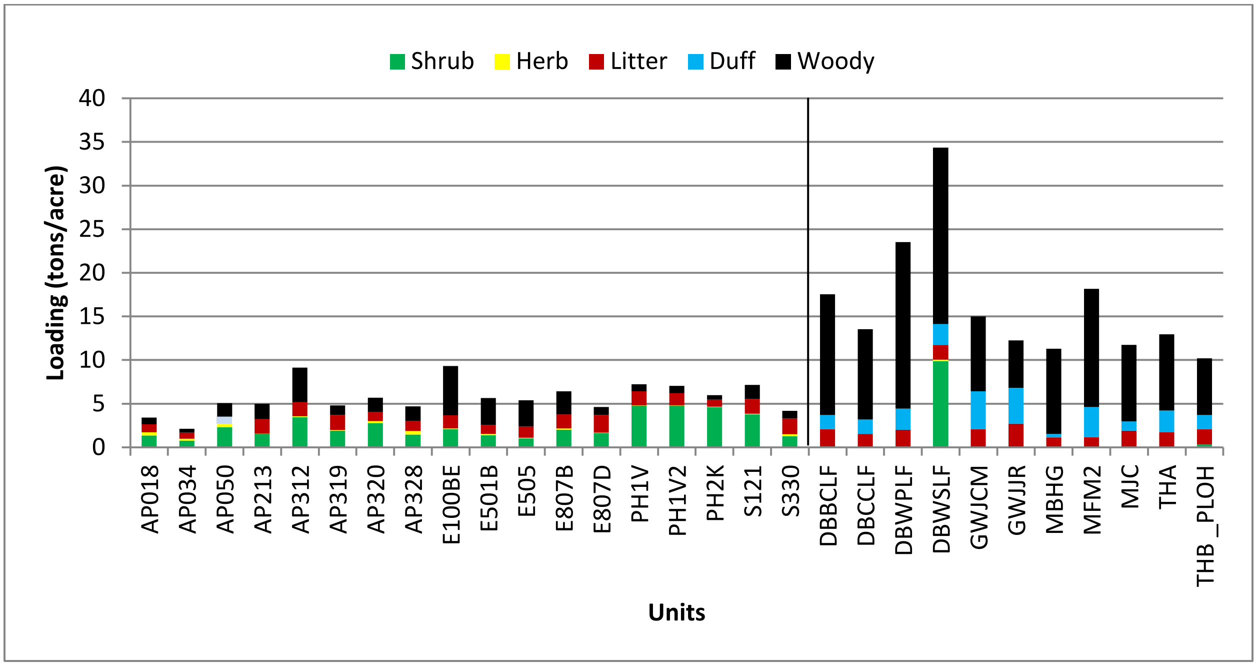


Figure 5. Loading by fuelbed category. Pine study sites are to the left of the vertical line.

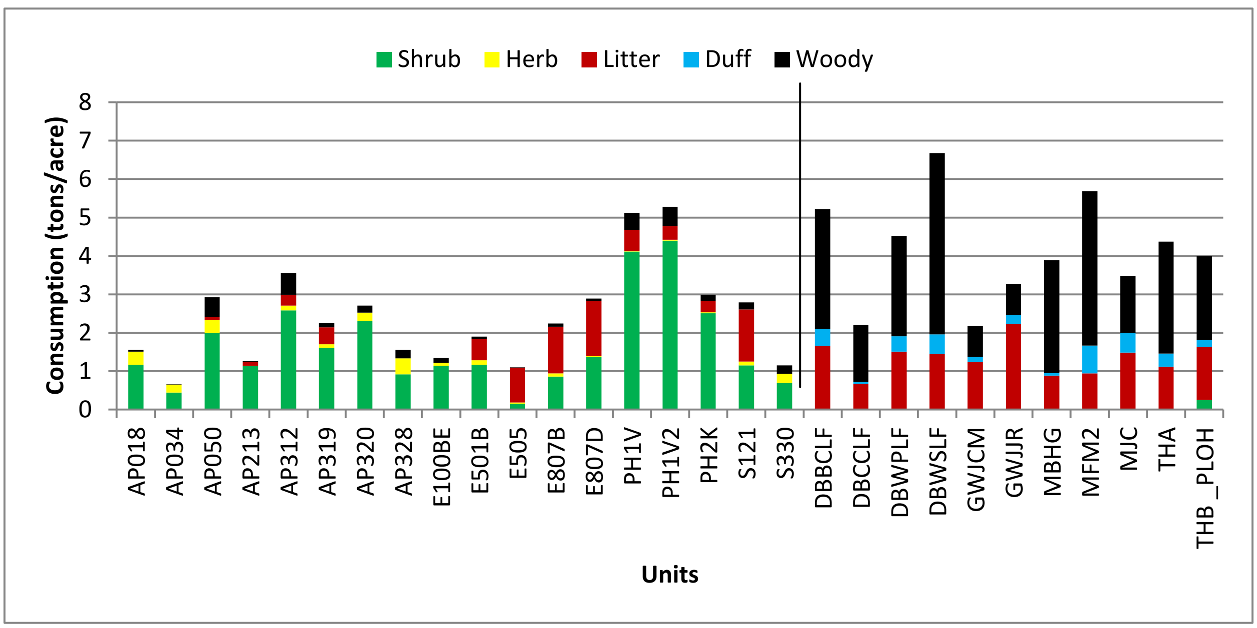


Figure 6. Fuel consumption by fuelbed category. Pine study sites are to the left of the vertical line.

B. Consumption Database Documentation

The fuel consumption database compiled for this study deliverable was created to store internal and test consumption datasets on prescribed and wildfire burns (Appendix 3). Over the past 30 years, FERA has conducted fuel consumption research in a variety of forest and shrubland types and under a range of prescriptions from broadcast burning of clearcut harvest units to prescribed burns in ponderosa pine and southern pine forests to boreal forest floor consumption in Alaska wildfires. The main objectives of creating this database were to (1) house all of our existing datasets in a single repository with common variable names and units of measure, and (2) allow for additional datasets to be added, including test data from published research.

As part of this present project to expand our understanding of fuel consumption in the East, we collected fuel consumption data (including pre- and post-burn fuel characteristics and day-of-burn environmental variables) for 29 burn units. This dataset expands on FERA's previous research in the Southeast (13 longleaf pine sites in Eglin Air Force Base, 5 loblolly pine sites in Sumter National Forest, and 31 flatwood shrub consumption sites throughout Florida). Consume 3.0 currently uses limited empirical models of woody fuel and forest floor consumption based on 18 southern pine sites. We plan to use this expanded dataset to improve our modeled fuel consumption for southern pine and mixed hardwood sites of the East.

To provide a test dataset of our revised eastern fuel consumption models, we compiled independent fuel consumption data from other studies in the eastern United States. We contacted fire and fuels experts from a range of agencies and universities in the East to locate and review potential test datasets (table 1).

Table 1. Eastern fuel consumption contacts and associated datasets

Contact	Organization	Dataset
Mary Arthur	University of Kentucky	Loucks thesis
John Blake	Savannah River Site	Scholl & Waldrup 2001
David Brownlie	U.S. Fish and Wildlife, Tallahassee	No data
Beth Buchanan	USFS	Very helpful with published literature
Matt Dickinson	USF Northern Research Station	Very helpful with published literature
Katherine Elliot	USFS Coweeta Hydrologic Laboratory	Has data on forest floor consumption – did not use.
Scott Goodrick	Retired Forest Service	Fuel consumption was not by fuelbed stratum.
Kevin Hiers	Eglin Air Force Base	Sullivan et al. 2003
Caroline Noble	Tall Timbers Research Station, NPS	Helpful, but we concluded FIREMON datasets didn't have enough day-of-burn weather.
Angie Reid	Tall Timbers Research Station	Unpublished – couldn't share until publication.

C. Fuel Consumption Comparison—Consume and FOFEM

Scatter plots presented in fig. 7 display predicted consumption by FOFEM and Consume compared to measured fuel consumption. A perfect fit between predicted versus measured consumption would be reflected in a linear regression model with an intercept of zero and slope of 1. This study encompassed markedly different vegetation types with 18 southern pine and 11 mixed hardwood units. Due to the relatively small sample size, we elected to pool the datasets. Examination of model residuals by plot suggest that with the exception of fine woody fuels, there are no discernible differences in model fit between the 18 pine sites and 11 mixed hardwood sites (fig. 8).

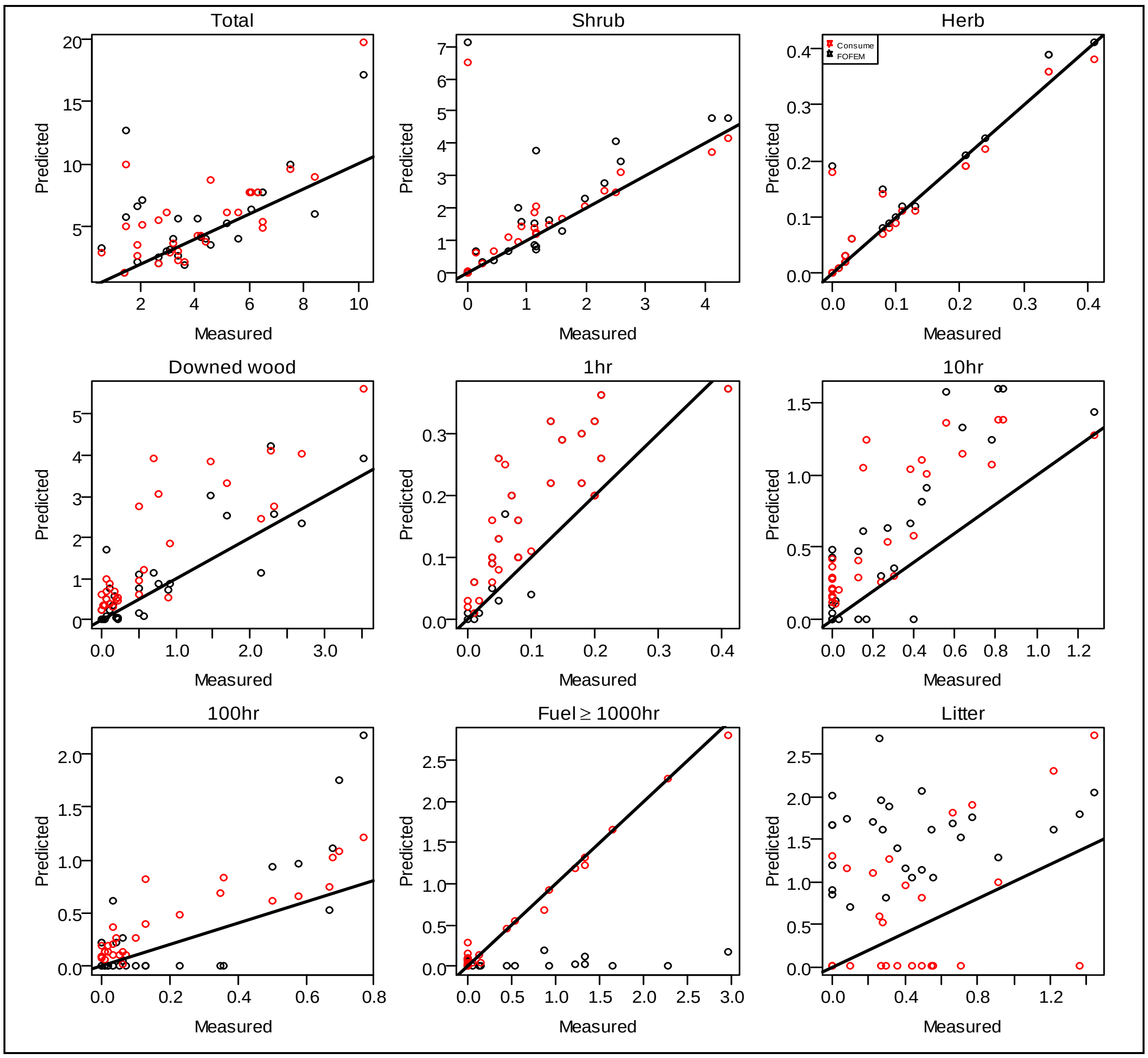


Figure 7. Predicted vs. measured fuel consumption (tons/acre) by total, shrub, herbaceous, all downed wood, 1-hr wood, 10-hr wood, 100-hr wood, ≥ 1000-hr wood, and litter. Red markers represent Consume 4.1 predictions, and black markers represent FOFEM predictions. Black lines represent a 1:1 fit (intercept = 0, slope = 1). Points above and below the black line indicate over-predictions and under-predictions respectively. Plots contain all data points, including model outliers.

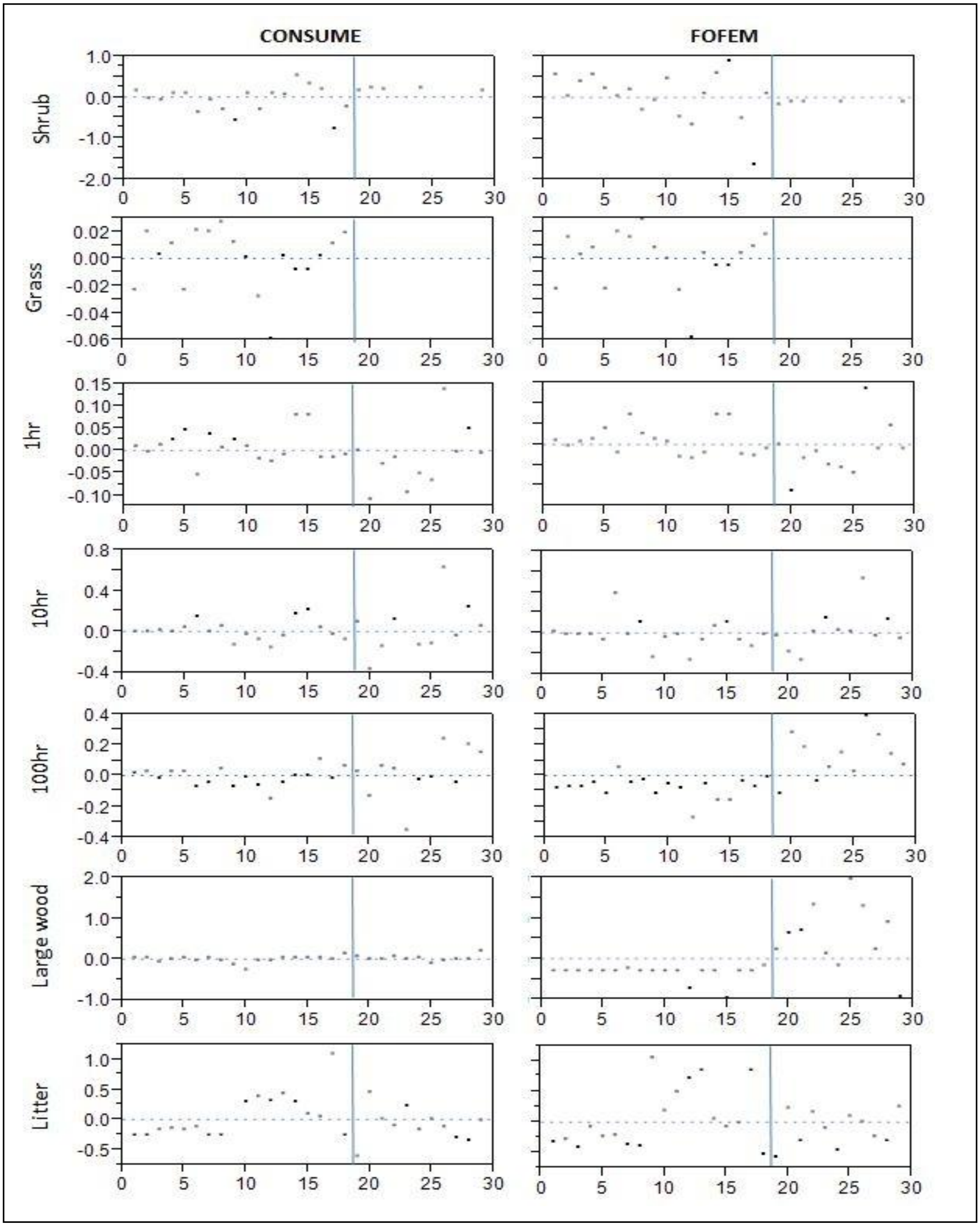


Figure 8: Model residuals by fuel category for Consume and FOFEM predictions. Units to the left of the line (1-18) are southern pine sites and to the right of the line (19-29) are mixed hardwood sites. Y-axis units are differences between predicted and actual fuel consumption (tons/acre).

The following is a summary of general trends and model behavior by each stratum.

Shrub consumption -- Consume and FOFEM predictions of shrub consumption correlate strongly with measured shrub consumption (table 3). Consume predictions are somewhat closer to measured consumption values with an R^2 of 0.94 compared to an R^2 of 0.81 for the FOFEM predictions.

Herbaceous consumption -- FOFEM and Consume accurately predicted herbaceous fuel consumption for 18 of the 29 units that contained an herbaceous vegetation layer. Both models predicted values that are strongly correlated ($R^{2\,=}$ 0.97) with measured herbaceous fuel consumption and with slopes near 1 and intercepts near zero. Only 18 of the 29 units had an herbaceous fuel layer, including all southern pine units and only one mixed hardwood unit. The mixed hardwood unit (DBWSLF) was excluded as an outlier because of its extremely low measured consumption versus modeled consumption. The Consume model predictions are equivalent with measured consumption at $\alpha = 0.1$.

1-hour fuel consumption – Both models tend to overpredict 1-hr fuel consumption, particularly for the mixed hardwood sites (fig. 5). Measured 1-hr fuel consumption ranges from 25 to 100%. Consume assumes that all 1-hr fuels will consume regardless of input fuel moisture, whereas FOFEM predictions vary by fuel moisture. FOFEM also predicted that the majority of units would have 100% 1-hr fuel consumption.

10-hour fuel consumption -- Both models overpredict 10-hr fuel consumption and are better at predicting the fuel consumption for the southern pine sites than the mixed hardwood sites (fig. 5). FOFEM has a slightly better fit with measured consumption than Consume ($R^2 = 0.75$ versus 0.65).

100-hour fuel consumption – Consume predictions of 100-hour fuel consumption have a better fit with measured consumption values ($R^2 = 0.81$) than FOFEM predictions ($R^2 = 0.66$). As with other fine wood categories, predictions are better for southern pine units than mixed hardwood units (fig. 5).

Large fuel consumption (>3 inch diameter) – Consume predictions of large wood consumption are highly correlated with measured consumption ($R^2 = 0.99$) with a nearly 1:1 model fit across all units and were found to be equivalent with measured consumption at $\alpha = 0.1$. FOFEM predictions consistently underpredict measured fuel consumption ($R^2 = 0.23$).

Litter consumption – Neither model does a good job at predicting litter consumption. FOFEM predicts 100% litter consumption for all sites whereas measured litter consumption ranges from 0 to 82%. Consume predictions are based on input litter depth (not loading), and are extremely low for litter depths less than 1 inch. Consume also predicts greater consumption than preburn loading for two units (E807B and E807D), partly due to a large discrepancy in calculated versus measured preburn loading.

Duff consumption—Consume and FOFEM predicted 0% duff consumption for the majority of mixed hardwood and pitch pine units. There was no duff present in the pine units due to their frequent burn rotation. Measured duff consumption in the mixed hardwood units ranged from 4 to 71% consumption.

D. Consume v 4.1

This fuel consumption data set for the eastern United States, and the statistical conclusions, led to minor changes to Consume that allow it to better predict consumption in the eastern United States. In recoding the Consume v 3.0 to v 4.1, we found a number of potential errors between the documentation and the code and instituted a comprehensive set of test equations. We corrected the following errors:

(1) We revised how natural and activity (logging slash) fuel litter and duff reduction are calculated. Litter and duff reduction are still not as responsive to fuel moisture as they probably should be, and will be adjusted further in 2012 when the Consume modular system becomes available.

(2) We corrected a coded conversion error in the heat release calculation.

3) We corrected an emission factor assignment error. We noted only activity fuel emissions factors were being used in Consume (as opposed to natural vs. activity).

4) We corrected how squirrel middens and basal accumulation loading and consumption are calculated in Consume.

This study has also helped motivate a re-architecture and reprogramming of Consume into a modular system that will allow easier adjustment to models internal to the system as additional validation sets become available. The reprogramming has been completed but the development of the modular system by Sonoma Technology for the Interagency Fuel Treatment Decision Support System (IFTDSS) and the assigned FERA workflow has been delayed until late 2012. This has not allowed implementation of the major changes to Consume as suggested by the Consume and FOFEM comparison manuscript. In 2012, we envision that this eastern United States validation dataset, in combination with a re-analysis of previous data collected from the United States, and the modular re-programming, will provide a more robust Consume for predicting fuel consumption during wildland fires. This will also serve as an improved fuel consumption module within the JFSP-supported IFT-DSS.

V. MANAGEMENT IMPLICATIONS

In the previous discussions of findings, the focus was on the 1) pre-fire and post fuel data collected, 2) creation of a data base, 3) evaluation of two currently used fuel consumption models for use in the eastern United States, and modification of Consume. The users of the data base and fuel consumption models include land managers, regulators, modelers and scientists. In this section we explore the management implications of this database, model comparison, and improvement of fuel consumption models.

A. Fuel load, fuel consumption, and environmental dataset from 29 prescribed burns in the Eastern United States.

As noted earlier, little research on wildland fuel consumption has been conducted in the eastern regions of the United States. Currently, best estimates from experience, the use of drought indices, or predictions from Consume and FOFEM are the methods used for estimating fuel consumption for prescribed fire planning and smoke management reporting. From anecdotal evidence and on the ground experience, managers believe Consume and FOFEM generally over-predict consumption of large woody fuels, litter, and duff. However, there are few if any reliable validation dataset in existence to assess the sensitivity, biases, and uncertainties of fuel consumption algorithms currently housed within Consume and FOFEM to see if these anecdotal observations are correct.

To correct this data gap, pre- and post fire and environmental data were collected from 29 sites to determine fuel consumption model uncertainties, biases, or application limits. The data is available to everyone and will allow managers to better estimate fuel consumption and predict fire effects, scientists to improve fuel consumption, emission production, and fire effects models, and regulators to evaluate emission inventory methodologies and assess carbon release. This data set has already been used as outlined in this final report to evaluate Consume and FOFEM for use in the eastern United States.

B. Fuel consumption data base

The study gathered other fuel consumption data sets from around the United States and compiled these sets in one data base for repository in SEMIP and the FERA website. The dataset is available to all scientists, modelers, regulators, and managers for testing and validating other fuel consumption systems currently being designed as well as moving our fuel consumption predictive capability forward and enable us to target the unique fuelbed types such as the ones found in the eastern United States forests.

C. Fuel Consumption Comparison—Consume and FOFEM

The study suggests that both Consume and FOFEM can be improved in there predictive equations of fine woody fuel, litter, and duff consumption for the eastern United States. This improvement will be made to Consume in 2012 once the Consume 4.1 module becomes available from Sonoma Technology. This information will also provide the developers of FOFEM with valuable information on how to improve FOFEM. Data also suggests that the apparent similarity in fuel characteristics and model predictions between the two major vegetation types sampled in this study (southern pine and mixed hardwood forest) indicate that with the exception of the fine woody fuels, it may be possible to combine existing consumption datasets to develop more robust predictive equations. Finally the evaluation will allow managers and regulators to improve their abilities to manage pollutant and carbon release since they understand the biases and uncertainties of the currently available consumption models.

With improved calibration procedures (Appendix 5, Kremens et al. 2011) and automated image analysis, prescribed-burn-scale estimates of fuel consumption and its variability can be made.

These estimates will provide evaluation data for Consume and FOFEM predictions, which provide stand or unit-scale average consumption.

D. Consume 4.1

The study suggests that Consume can be improved in the predictive equations of fine woody fuel, litter, and duff consumption for the eastern United States. This will enable FERA scientists to target models that need improved functionality for specific fuelbed categories once the Consume 4.1 module is available from Sonoma Technology Inc.

VI. RELATIONSHIP TO OTHER RECENT FINDINGS AND ONGOING WORK

Fuel consumption is a key element in predicting emissions generated from wildland fires and the associated air quality impacts. Because the majority of state smoke management programs require an estimate of emissions to allow a prescribed fire to be conducted, it is critical to understand the predictive capabilities of our fuel consumption models. This project provides a consumption validation dataset that:

- Enabled testing of fuel consumption modeling efforts such as the First Order Fire Effects Model (FOFEM) (JFSP 98-1-08-03) and Consume 3.0 (JFSP 98-1-9-06)
- Provided improved uncertainties existing in other smoke management models and carbon production models that require fuel consumption inputs such as BlueSky (JFSP 06-1-1-12, 07-2-1-60) Fire Emission Production Simulator (JFSP: 98-1-9-05), VSMOKE (Lavdas 1996), Wildfire Emissions Information System (French, et. al. 2011)
- A dataset to be submitted to the SEMIP and/or FRAMES repositories for use by all.
- Methods and technology for airborne and in-fire monitoring were developed under NASA grants to Rochester Institute of Technology (NASA /FIRES, NASA/WASP and NASA/ISSI) and a JFSP rapid response grant (Lentile, et al. 2007, JFSP 03-S-01). Further development and application are being conducted under an current JFSP-funded project, Fuel Consumption and Smoke Emissions from Landscape-Scale Burns in Eastern Hardwoods (06-2-1-33,). Appalachian mixed-oak fuel (Ohio and Kentucky) consumption data will be provided as an independent validation dataset by the latter project.

VII. FUTURE WORK NEEDED

Sites with a heavy fuel load or which burn under extreme fire conditions were not included in this study. Additional work is needed to improve the validation data set by targeting such sites. This would provide fuel consumption values in the dataset that would allow validation of models for extreme fuel consumption situations. These are the situations that can occur during wildfires and, in certain cases, prescribed fires, which are a major contribution to smoke impacts.

The data from the study suggests that both Consume and FOFEM can be improved in their predictive equations of fine woody fuel, litter, and duff consumption for the eastern United

States. Because Consume is being modified into a modular system, the next step will be to implement the results of this study and continue to improve the system to better represent the eastern United States.

VIII. SCIENCE DELIVERY AND APPLICATION

There is tremendous interest among regional land managers and smoke management regulatory agencies in improving estimates of smoke from wildland fire as public concerns about smoke impacts continue to jeopardize prescribed burning programs (Cursio 2011, Brenner, 2011, Hiers, 2011). The science delivery is particularly relevant to managers in two ways: (1) managers are expected to complete the development of the Smoke Management Plans for their states during the course of this project and (2) much of the science delivery will be focused on management units for which the participants themselves are responsible. The deliverables have included: (a) a final report to JFSP; (b) a fuel consumption validation data set and Microsoft Excel spread sheet that represents prescribed burning and monitoring of 29 units in the eastern regions of the United States; (c) a fuel consumption validation database that includes a data set of monitored fuel consumption collected for this study, and a compiled data set of fuel consumption data available from other studies in the eastern and western United States; (d) a draft refereed paper on the a first-principles calibration method for airborne and ground based infrared measurements; (e) ortho-geo-rectified WASP imagery for eight fires in Ohio, Kentucky, and Florida; (f) a non-refereed draft manuscript that defines the uncertainties and biases related to the fuel consumption equations internal to Consume and FOFEM; (g) two 12-hour regional fuels workshop in the eastern region teaching the Consume; and (h) two websites were implemented for conveying the validation data set and information about this study (table 2). Although a complete reprogramming of Consume has been completed and tested, it was decided to delay the release of Consume 4.1 until September, 2012 to coincide with the workflow release of IFT-DSS and allow additional refinement to better represent eastern United States fuelbeds.

There were several additional deliverables that were completed beyond what was identified in the original proposal. These included measuring fuel consumption on 9 additional units, and leading five 8-hour fuel workshops, four 4-hour workshops, and 35 training sessions (table 3).

Table 2. Comparison of proposed and actual deliverables

Proposed	**Delivered**	**Status**
Final	Final report. *This is in partial fulfillment of JFSP project # 08-1-6-01.*	Complete
Dataset	Summary data tables for study. These data tables are located in appendix 1 of the final report and contain several data tables summarizing the fuel consumption validation dataset from the 29 units monitored in the eastern region of the United States. It includes study site descriptions and location, pre-fire environmental variables, and pre-fire loading and fuel consumption by fuelbed category. *This is in partial fulfillment of JFSP project # 08-1-6-01.* Attached to this report as Appendix 1. Attached JFSP_08-1-6-01_consumption _data_tables__app1.pdf	Complete
Dataset	Eastern fuel consumption study data spread sheet for all data collected on the 29 units monitored. It includes study site descriptions and location, pre-fire environmental variables, fuel moisture content weather, and pre-fire loading and fuel consumption by fuelbed category. *This is in partial fulfillment of JFSP project # 08-1-6-01 and is being deposited in the SEMIP repository and is posted on the Fire and Environmental Research Application Team's website: http://www.fs.fed.us/pnw/fera/* Attached database: JFSP_08-1-6-01_ unit_data.xlsx. Documentation attached to this report as Appendix 2. Attached documentation: JFSP_08-1-6-01_consumption _dataset_documentation_app2.pdf	Complete
Database	Fuel consumption validation dataset. This Access database is described in Appendix 3 and includes a data set of the monitored fuel consumption collected for this study and a compiled data set of fuel consumption data available from other studies in the eastern and western United States. *This is in partial fulfillment of JFSP project # 08-1-6-01 and is being deposited in the SEMIP repository and is posted on the Fire and Environmental Research Application Team's*	Complete

	website: http://www.fs.fed.us/pnw/fera/. Attached: JFSP_08-1-6-01_consumption_database_app3.mdb Documentation attached to this report as Appendix 3. Attached documentation: JFSP_08-1-6-01__consumption_database_documentation_app3.pdf	
Dataset	List of ground-calibration datasets, summarized to total ground-leaving energy from the fires measured during this study. Included are total energy calculated from dual-band radiometry (Kremens et al. 2010) and from the restricted bandpass LWIR detectors as described by Kremens and Dickinson (in review, Appendix 5). The plot indicates that the physics-based simulation approach as discussed in the in Kremens and Dickinson (in review, Appendix 5) has validity, relating the well-understood dual-band method of estimating energy to energy inferred from a detector with a single, limited bandpass. The next step is to validate the calibration approach with ground-based data. *This is in partial fulfillment of JFSP project # 08-1-6-01.* Dataset attached to this report as Appendix 4. Documentation attached to this report as Appendix 3. Attached documentation: JFSP_08-1-6-01__ground_consumption_calibration_dataset_ app4.pdf	Completed
Refereed Publication	A manuscript sufficient for publication in a peer-reviewed journal outlet on the airborne data collected. Kemens, Robert L.; Dickinson, Matthew B. 20xx. Flame-front scale numerical simulation of wildland fire radiant emission spectra as an aid to observation of wildland fire. Draft manuscript for submission to International Journal of Wildland Fire.*This is in partial fulfillment of JFSP Project Number 08-1-6-01.* Attached: JFSP_08-1-6-01_Kemens_draft_manuscript_app5.pdf	Draft complete; publication expected December 2012
Non-Refereed	Draft manuscript on the statistical comparison between	Draft complete;

Publication	Consume 3.0 and FOFEM. Prichard, Susan, Karau, Eva, Ottmar, Roger, Wright, Clint. 20xx. A comparison of the Consume and FOFEM fuel consumption models using field data collected in the southeastern United States. Internal review complete. This manuscript will be submitted as a PNW Research Note. *This is in partial fulfillment of JFSP Project Number 08-1-6-01.* Attached: 01_Prichard_draft_manuscript_app6.pdf.	publication expected December 2012
Computer Model /Software/Algorithm	Revisions of Consume v 3.0 to Consume v 4.1. Consume v 3.0 was reprogrammed into Python programming language and tested for modular implementation into IFT-DSS and FERA tools workflow. Errors found during testing were corrected. In addition, Consume was slightly modified to improve consumption models to better represent fuelbeds found in the eastern United States. This version is Consume v. 4.1. Modification will continue as the validation data and future data is further analyzed. It was decided to delay the release of Consume 4.1 until September, 2012 to coincide with the workflow release of IFT-DSS and allow additional refinement to better represent eastern United States fuelbeds. *This is in partial fulfillment of JFSP project # 08-1-6-01.* Posted: http://www.fs.fed.us/pnw/fera/research/smoke/consume/index.shtml	Partially complete, full completion and release expected September 2012 to coincide with IFT-DSS.
Nonreferred draft publication and Consume tutorial	Since model refinement was minimal and major changes will be forthcoming in 2012 as Sonoma Tech provides the FERA tool integrated workflow, no changes were implemented to the current user's guide or tutorial. It will be modified and released with the release of the FERA tool workflow within IFT-DSS. When complete, it will be provided to the JFSP website. *This is in partial fulfillment of JFSP project # 08-1-6-01.* Current Consume v 3.0 User's Guide is posted at: http://www.fs.fed.us/pnw/fera/research/smoke/consume/consume30_users_guide.pdf. Consume v 3.0 tutorial is posted at: http://www.fs.fed.us/pnw/fera/research/tutorials/consume.shtml	Postponed until September, 2012 to coincide with Consume 4.1 release
Training Session	Two 12-hour fuel workshops at Kinston, NC, December 2009, and January 2011.	Complete

Web Page	Two web pages developed for this study including the home page for the study and Consume. They are located on the FERA website. Posted: http://www.fs.fed.us/pnw/fera/research/smoke/consumevalidation.shtml http://www.fs.fed.us/pnw/fera/research/smoke/consume/index.shtml	Complete

Table 3. Additional deliverables completed that were not included in the original proposal.

Additional Deliverables Completed But Not Originally Proposed	**Status**
Nine additional units monitored for fuel consumption beyond the 20 that were proposed.	Completed
• Over 35 Consume presentations and exercises at RX410 (Smoke Management) and RX310 (Fire Effects) national and regional training sessions • One 3-day workshop for Forest Service, Pacific Northwest Region • Two 8-hr and one 4-hr 401-series workshops at the University of Idaho • Three 8-hr and two 4-hour workshops at Technical Fire Management training • Three 4-hour workshops given at conferences (4th Fire Congress in Savannah, GA, 2009; Mixed severity fire regime: Ecology and Management Conference, Spokane, WA, 2010; Interior West Fire Ecology Conference, Snowbird, UT, 2011).	Completed

WEB PAGE

A web page including project progress was established in 2009 at http://www.fs.fed.us/pnw/fera/research/smoke/consumevalidation.shtml

A web page on Consume has been updated and is located at http://www.fs.fed.us/pnw/fera/research/smoke/consume/index.shtml

POSTERS, ABSTRACTS, AND PRESENTATIONS

Jon E. Dvorak, Cameron S. Balog, Robert E. Vihnanek, and Roger D. Ottmar. Stereo photo series for quantifying natural fuels: Post-hurricane fuels in forests of the southeast United States. Poster presentation, 4th International Fire and Ecology Management Conference, Savannah, GA, November 30-December 4, 2009

Kremens, Robert L. 2009. Infrared techniques pplied to fire science. Invited presentation at the Rocky Mountain research Station Missoula Fire Laboratory.

Kremens, Robert L. 2010. A short review of data collection instruments and techniques for measuring total power and energy. Invited presentation at the Rocky Mountain research Station Missoula Fire Laboratory.

PUBLICATION

Draft manuscript: Kremens, Robert; and Dickinson, Mathew. Flame-front scale numerical simulation of wildland fire radiant emission spectra as an aid to observation of wildland fires. *Attached as Appendix 5.*

Draft manuscript: Prichard, Susan; Karau, Eva; Ottmar, Roger; Wright, Clint. [N.d.]. A comparison of the Consume and FOFEM fuel consumption models using field data collected in the southeastern United States. Proposed outlet: U.S. Forest Service, Pacific Northwest Research Station, Research Note. *Attached as Appendix 6.*

CONSUME DEMONSTRATIONS AND WORKSHOPS

- Smoke Modeling Workshop, Kinston, NC, 2009, 2011
- Technical Fire Management, Bothell, WA, 2009, 2010, 2011
- Rx410, Albuquerque, Redmond, Missoula, Boise, Denver, Tallahassee, 2009, 2010, and 2011 Rx410 Grand Rapids, MN 2009, 2011
- University of Idaho, 2009, 2010
- Joseph Jones Ecological Research Center Regional Fuels Workshop, Ichauway, GA, 2008, 2009
- US Forest Service Region 6, 3-day regional fuels workshop, Redmond, OR 2009
- Savannah Fire Congress Conference, Savannah, GA, 2009
- Mixed Severity Fire Regimes, Ecology and Management Conference, Spokane, WA, 2010
- Interior West Fire Ecology Conference, Snowbird, UT 2011
- Fire Behavior Conference Workshop, Coimbra, Portugal, 2010

CONSULTATIONS

Over the past three years, the principle investigator consulted with many land managers, regulators, and scientists with regard to Consume and consumption equations. These included fuel and fire managers of the USDI Fish and Wildlife Service and National Park Service, US Forest Service, Department of Defense, Army and Air Force, and the Division of Forestry in the States of Georgia, Florida, North Carolina, South Carolina, Ohio, Virginia, and Kentucky. The co-principal investigator has consulted on fuel consumption and fire behavior with fuel and fire managers at the Daniel Boone National Forest, Ohio Department of Natural Resources, and Mammoth Cave National Park.

TUTORIAL

A web-based self-taught tutorial along with an instructor's guide and student workbook for the Consume was developed (JFSP 04-4-1-19) and **was not updated** because the changes in Consume were minor and the tutorial did not need to be modified to account for the changes. The Consume 4.1 tutorial can be accessed through a web-browser or down-loaded directly from http://www.fs.fed.us/pnw/fera/products/tutorials/.

LESSON PLANS AND TRAINING

The use of Consume has been implemented into the lesson plan that was developed for the RX-410 Smoke management, and RX 310, Fire Effects, lessons. Finally, Consume has been added to the University of Idaho's 401 fuels management series and into the Technical Fire Management (TFM) fuels module.

TRAINING

The principal investigator taught how to use Consume approximately 35 times at both mational and regional training sessions as well as at five regional workshops.

ACKNOWLEDGEMENTS

We thank the Joint Fire Science Program for the financial assistance in providing the opportunity to complete this comparison and thank our cooperators including John Ashcraft, Mammoth Caves National Park; Bob Broyles and Mike Bowden, Ohio Division of Forestry; Jeffrey Lewis and EJ Bunzendahl, Daniel Boone National Forest; Steve Smestad and Steve Croy, George Washington and Jefferson National Forest; Eugene Watkins, Apalachicola National Forest; Greg Titus, St. Marks National Wildlife Refuge; and Kevin Heirs and Brett Williams, Jackson Guard, Eglin Air Force Base. We also thank Jon Dvorak, Shawn Smith, Travis Freed, Jon McDuffey, Joe Restaino, Cameron Balog, Aarin Sengsirirak, Jim Cronan, and Bill Borovicka for their hard work in collecting the data. Finally, we greatly appreciate Maureen Kennedy who provided guidance on the statistical analysis.

LITERATURE CITED

Albini, F.A. 1994. Program Burnup: A simulation model of the burning of large woody natural fuels. Unpublished final report for Research Grant INT-92754-GR. On file at the USDA, Forest Service, RMRS, Missoula Fire Science Laboratory, Missoula, MT.

Albini, F.A.; Reinhardt, E.D. 1995. Modeling ignition and burning rate of large woody natural fuels. International Journal of Wildland Fire. 5(2):81-91.

Albini, F.A.; Brown, J.K.; Reinhardt, E.D.; Ottmar, R. D. 1995. Calibration of a large fuel burnout model. International Journal of Wildland Fire. 5(3):173-192.

Albini, F.A.; Reinhardt, E.D. 1997. Improved calibration of a large fuel burnout model. International Journal of Wildland Fire. 7(1):21-28.

Beaufait, William R.; Hardy, Charles, E.; Fisher, William C. 1977. Broadcast burning in larch-fir clearcuts: The Miller Creek-Newman Ridge study. Res. Pap. INT-175, US Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT. 73 p.

Brenner, Jim. 2011. Personal communications, July, 2011, Florida Forest Service, Tallahassee, FL.

Brown, J.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.

Cursio, Gary, 2011. Personal communications, January, 2011, Department of Forest Resources, Kingston, North Carolina.

French, Nancy H.F.; de Groot, William J.; Jenkins, Liza K.; Rogers, Brenden M; Alvarado, Ernesto; Amiro, Brian; de Jong, Bernardus; Goetz, Scott; Hoy, Elizabeth; Hyer, Edward; Keane, Robert; Law, B.E.; McKenzie, Donald; McNulty, Steven G.; Ottmar, Roger; Perez-Salicrup, Diego R.; Randerson, James; Robertson, Kevin M.; Turetsky,Merritt. 2011. Model comparisons for estimating carbon emissions from North American wildland fire. Journal of Geophysical Research Bioscience. 116: 1-21.

Hiers, Kevin. 2011. Personal communications, February, 2011. Jackson Guard, Eglin Air Force Base, Niceville, FL

Joint Fire Science Program. 2009. Consume 3.0--a software tool for computing fuel consumption**.** Fire Science Brief. 66, June 2009. 6 p.

Kremens, R.L.; Smith, A.M.; Dickinson, M.B. 2010. Fire Metrology: Current and future directions in physics-based measurements., Fire Ecology, 6, pp. 13-35.

Kremens, R. L., Dickinson, M. B., Bova, A. S. 2011. Radiant flux density, energy density, and fuel consumption in mixed-oak forest surface fires. International Journal of Wildland Fire, accepted.

Lavdas, Leonidas G. 1996. Program VSMOKE—Users Manual. Gen. Tech. Rep. SRS-6. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 156 p.

Lentile, Leigh; Morgan, Penny; Hardy, Colin; Hudak, Andrew; Means, Robert; Ottmar, Roger; Robichaud, Peter, Sutherland, Elaine, Ways, Frederick, Lewis, Sarah. 2007.

Lessons learned from rapid response research on wildland fires. Fire Management Today. 6 (1): 24-31.

Marshall, D.J., Wimberly, M., Bettinger, P. Stanturf, J. 2008. Synthesis of knowledge of hazardous fuels management in loblolly pine forests. GTR-SRS-110, U.S. Forest Service, Southern Research Station, Asheville, NC.

Ononye, A., A. Vodacek, Y. Li, and Z. Wang. 2005. Mapping of active fire area by image gradient technique using multi-spectral imagery. In: Remote Sensing for Field Users. Proc. 10th Biennial USDA Forest Service Remote Sensing Applications Conference. Salt Lake City, UT. CD-ROM, ISBN 1-57083-075-4, ASPRS

Ottmar, Roger D.; Vihnanek, Robert E. 2000. Stereo photo series for quantifying natural fuels. Volume VI: Longleaf pine, pocosin, and marshgrass types in the Southeast United States. PMS 835. Boise, ID: National Wildfire Coordinating Group, National Interagency Fire Center. 56 p. Order Number – NFES #2630

Ottmar, Roger D.; Vihnanek, Robert E.; Mathey, Jared W. 2003. Stereo photo series for quantifying natural fuels. Volume VIa: sand hill, sand pine scrub, and hardwood with white pine types in the Southeast United States with supplemental sites for Volume VI. PMS 838. Boise, ID: National Wildfire Coordinating Group, National Interagency Fire Center. 78 p. Order Number – NFES #1119

Ottmar, R.D.; Sandberg, D.V.; Riccardi, C.L.; Prichard, S.J. 2007. An overview of the Fuel Characteristic Classification System – quantifying, classifying, and creating fuelbeds for resource planning**.** Canadian Journal of Forest Research. 37(12): 2383-2393.

Prichard, S.J.; Ottmar, R.D.; Anderson, G.K. 2007. Consume user's guide and scientific documentation (online) http://www.fs.fed.us/pnw/fera/research/smoke/consume/consume30_users_guide.pdf

Reinhardt, E. 2003. Using FOFEM 5.0 to estimate tree mortality, fuel consumption, smoke production and soil heating from wildland fire. Presentation at the 2nd International Wildland Fire Ecology and Fire Management Congress, 16-20 November 2003, Orlando, FL. 6 p.

Reinhardt, E.D.; Keane, R.E.; Brown, J.K. 1997. First Order Fire Effects Model: FOFEM 4.0, user's guide. U.S. For. Serv. Gen. Tech. Rep. INT-GTR-344.

Robinson, A.P.; Froese, R.E. 2004. Model validation using equivalence tests. Ecol. Model. 176: 349-358.

Robinson, A.P.; Duursma, R.A.; Marshall, J.D. 2005. A regression-based equivalence test for model validation: shifting the burden of proof. Tree Phys. 25: 903-913.

Theobald, D.M., Romme, W.H. 2007. Expansion of the U.S. wildland-urban interface. Landscape Urban Plan. 83, 340-354.

Wade, D.D.; Lunsford, J.D. 1989. A guide for prescribed fire in southern forests.US Forest Service, Southern Region Technical Publication R8-TP-11, Atlanta, GA.

Wright, C.; Eagle, P. 2011. The digital photo series. JFSP project 04-4-1-01. http://depts.washington.edu/nwfire/dps/

Zhang, Y. He, H.S., Yang, J. 2008. The wildland–urban interface dynamics in the southeastern U.S. from 1990 to 2000. Landscape Urban Plan. 85: 155-162.

Appendices 1-6--Final Report

JFSP Project # 08-1-6-01

Appendix 1: Eastern Fuel Consumption Data Study Summary—JFSP Project # 08-1-6-01

Eastern fuel consumption study data summarized for the 29 units monitored. It includes study site descriptions and location, pre-fire environmental variables, and pre-fire loading and fuel consumption by fuelbed category. Unshaded rows are pine units and shaded rows are mixed hardwood units.

Attached to JFSP website: JFSP_08-1-6-01_consumption _data_tables__app1.pdf

Unit Label and Description

Unit code	Location	Latitude	Longitude	Burn date	Fuelbed type	Ignition type	Ignition length (min)	Site description
AP018	Appalachicola NF, FL	30.2089	-84.8599	2/11/2010	Pine	Helicopter	3.75	Long leaf pine plantation with understory of palmetto, gallberry, other shrub and grass.
AP034	Appalachicola NF, FL	30.2026	-84.8345	2/18/2010	Pine	Hand	4	Same as AP018
AP050	Appalachicola NF, FL	30.1375	-84.7746	2/7/2009	Pine	Helicopter	360	Same as AP018
AP213	Appalachicola NF, FL	30.3423	-84.5412	2/11/2010	Pine	Hand	2.75	Same as AP018
AP312	Appalachicola NF, FL	30.1957	-84.6313	1/24/2009	Pine	Helicopter	120	Same as AP018
AP319	Appalachicola NF, FL	30.2184	-84.4205	1/14/2010	Pine	Hand	3.25	Same as AP018
AP320	Appalachicola NF, FL	30.2432	-84.4685	2/17/2009	Pine	Helicopter	240	Same as AP018
AP328	Appalachicola NF, FL	30.1309	-84.6327	1/31/2009	Pine	Helicopter	240	Same as AP018
E100BE	Eglin AFB, SC	30.6566	-86.7145	1/12/2010	Pine	Hand	4	Same as AP018
E501B	Eglin AFB, SC	30.4569	-86.7618	12/23/2009	Pine	Hand	5.75	Same as AP018
E505	Eglin AFB, SC	30.4614	-86.6688	1/23/2010	Pine	Hand	1.75	Same as AP018
E807B	Eglin AFB, SC	30.4847	-86.2767	1/4/2010	Pine	Hand	2.5	Same as AP018
E807D	Eglin AFB, SC	30.5034	-86.2570	2/21/2010	Pine	Hand	5	Same as AP018
PH1V	Pumpkin Hill State Park Reserve, FL	30.4729	-81.4926	2/10/2009	Pine	Hand	240	Pond pine forest with understory of sand live oak, palmetto, and wiregrass
PH1V2	Pumpkin Hill State Park Reserve, FL	30.4729	-81.4926	2/27/2009	Pine	Hand	270	Same as PH1V
PH2K	Pumpkin Hill State Park Reserve, FL	30.4719	-81.4897	2/27/2009	Pine	Hand	135	Pond pine savannah with patchy understory of palmetto and oak interspersed with bare mineral soil
S121	Saint Marks Wildlife Refuge, FL	30.1433	-84.1317	3/19/2009	Pine	Hand	60	Long leaf pine forest with understory dominated by palmetto component with some oak species.
S330	Saint Marks Wildlife Reserve, FL	30.0783	-84.3743	2/17/2010	Pine	Hand	4	Long leaf pine forest with understory of palmetto, gallbery, and wiregrass
DBBCLF	Daniel Boone NF, KY	38.0526	-83.5543	4/18/2009	Hardwood	Helicopter	270	Mixed hardwood forest with open greenbriar understory
DBCCLF	Daniel Boone NF, KY	38.0435	-83.5500	4/18/2009	Hardwood	Helicopter	390	Mixed hardwood forest with understory of red maple and greenbrier.
DBWPLF	Daniel Boone NF, KY	38.0608	-83.5802	4/17/2009	Hardwood	Helicopter	210	Same as DBBCLF
DBWSLF	Daniel Boone NF, KY	38.0882	-83.5783	3/23/2009	Hardwood	Hand	300	Mixed forest, with hardwood species, shortleaf pine, and pitch pine. Understory dominated by red maple and greenbrier.
GWJCM	George Washington & Jefferson NF, VI/KY	37.7554	-79.2114	4/9/2009	Hardwood	Hand.	300	Mixed hardwood forest with red maple understory.
GWJJR	George Washington & Jefferson NF, VI/KY	38.1350	-79.7911	4/17/2009	Hardwood	Helicopter	285	Same as GWJCM
MBHG	Mammoth Caves NP, KY	37.1811	-86.0999	3/31/2009	Hardwood	Hand	360	Mixed hardwood forest with little to no understory.
MFM2	Mammoth Caves NP, KY	37.2093	-86.0816	4/1/2009	Hardwood	Hand	360	Mixed hardwood forest with a midstory of maple, dogwood, and cedar. Little to no understory.
MJC	Mammoth Caves NP, KY	37.1763	-86.1134	4/2/2009	Hardwood	Hand	480	Same as MFM2
THA	Tar Hollow State Park, OH	39.3660	-82.7770	4/13/2009	Hardwood	Helicopter	270	Mixed hardwood forest with a midstory of maple and American beech. Little to no understory.
THB PLOH	Tar Hollow State Park, OH	39.3490	-82.7580	4/13/2009	Hardwood	Helicopter	90	Mixed hardwood forest with heavy greenbriar understory.

Environmental Variables

Unit	Fuel Moisture								Wind speed	Days since rain
	Shrub	Grass	1 hr	10 hr	100 hr	1000 hr	Litter	Duff		
	Percentage								*Miles per hour*	*Days*
AP018	--	33.6	14.1	61.4	--	--	23.0	--	2.0	33.6
AP034	103.9	35.7	12.3	74	71.3	--	24.6	--	2.0	35.7
AP050	120.1	38.6	8.5	22.6	93.4	93.0	15.9	--	--	38.6
AP213	93.7	28.0	10.2	54.9	78.8	N/A	19.1	--	2.0	28.0
AP312	108.3	60.4	23.4	56	63.7	101.0	35.4	--	--	60.4
AP319	114.3	43.1	15.4	48.9	58.1	--	23.4	--	--	43.1
AP320	101.0	31.0	16.9	60.3	77.1	84.2	31.8	--	--	31.0
AP328	92.8	34.1	18.5	56.4	67.3	65.6	15.8	--	--	34.1
E100BE	100.3	48.5	27.1	40	69.8	123.09	18.8	--	4.0	48.5
E501B	--	--	--	--	--	--	--	--	5.0	--
E505	97.0	45.5	20.5	66.5	129.5	113.8	21.2	--	2.0	45.5
E807B	--	--	--	--	--	--	--	--	3.0	--
E807D	101.6	40.3	17.7	81.2	210.1	140	34.5	--	6.0	40.3
PH1V	94.1	36.5	9.8	13.7	60.5	--	6.1	--	--	36.5
PH1V2	94.1	36.5	9.8	9.89	60.5	--	6.1	--	--	36.5
PH2K	54.5	21.7	8.4	9.89	27.3	--	25.1	--	--	21.7
S121	80.3	67.7	13.8	32	106.4	--	21.5	--	--	67.7
S330	92.6	26.9	21.9	57.5	346.7	--	18.9	--	1.0	26.9
DBBCLF	--	--	8.6	13.7	51.6	69.5	6.4	75.2	--	--
DBCCLF	--	--	13.9	42.6	7.9	58.2	47.8	172.9	--	--
DBWPLF	--	--	13.6	23.2	58.5	82.45	5.7	191.1	--	--
DBWSLF	--	--	11	20.3	66.7	67.5	7.9	77.9	--	--
GWJCM	--	--	25.9	50.3	59.3	73.5	43.3	349.5	--	--
GWJJR	--	--	11	39.6	69.3	73.34	9.1	272.9	--	--
MBHG	--	--	17.6	34.7	45	57.9	11.9	--	--	--
MFM2	--	--	38.6	25.7	--	71.9	6.76	--	--	--
MJC	--	--	11.2	27.3	51.4	76.3	5.7	67.49	--	--
THA	--	--	8.1	9.64	18.6	59.1	9.7	59.67	--	--
THB PLOH	--	--	7.3	13.1	30.5	52.1	7.9	47.2	--	--

Fuel Loading

Unit	Shrub	Herb	Litter	Duff	1 hr	10 hr	100 hr	1000+ hr	Total Woody	Total
	Tons per acre									
AP018	1.34	0.39	0.91	NP	0.03	0.24	0.17	0.34	0.78	3.42
AP034	0.76	0.21	0.71	NP	0.02	0.17	0.14	0.11	0.44	2.12
AP050	2.29	0.39	0.84	NP	0.22	0.63	0.35	0.34	1.74	5.26
AP213	1.57	0.01	1.66	NP	0.01	0.14	0.32	1.27	1.07	4.31
AP312	3.44	0.12	1.61	NP	0.16	0.67	0.97	2.16	1.54	6.71
AP319	1.89	0.09	1.74	NP	0.10	0.18	0.26	0.53	3.96	7.68
AP320	2.79	0.21	1.04	NP	0.11	0.18	0.49	0.86	1.64	5.68
AP328	1.46	0.41	1.19	NP	0.08	0.33	0.24	0.98	1.63	4.69
E100BE	2.07	0.08	1.53	NP	0.1	0.43	0.64	4.46	5.63	9.31
E501B	1.4	0.12	1.05	NP	0.06	0.23	0.34	2.46	3.09	5.66
E505	1.04	0.06	1.29	NP	0.06	0.32	0.48	2.13	2.99	5.38
E807B	2	0.15	1.61	NP	0.13	0.48	0.93	1.11	2.65	6.41
E807D	1.65	0.02	2.05	NP	0.09	0.25	0.46	0.1	0.9	4.62
PH1V	4.77	0.03	1.61	NP	0.2	0.3	0.22	0.09	0.81	7.22
PH1V2	4.77	0.03	1.39	NP	0.2	0.35	0.22	0.09	0.86	7.05
PH2K	4.62	0.02	0.81	NP	0.16	0.13	0.05	0.19	0.53	5.98
S121	3.76	0.1	1.66	NP	0.1	0.47	0.33	0.72	1.62	7.14
S330	1.27	0.24	1.8	NP	0.03	0.33	0.25	0.27	0.88	4.19
DBBCLF	0.06	NP	2.01	1.65	0.32	1.59	3	8.92	13.83	17.55
DBCCLF	0.01	NP	1.52	1.65	0.26	1.21	2.08	6.8	10.35	13.53
DBWPLF	0.04	NP	1.96	2.44	0.29	1.57	2.53	14.68	19.07	23.51
DBWSLF	9.87	0.19	1.68	2.38	0.36	1.59	2.69	15.6	20.24	34.36
GWJCM	NP	NP	2.07	4.36	0.25	1.43	2.03	4.87	8.58	15.01
GWJJR	0.02	NP	2.68	4.14	0.2	1.2	1.2	2.81	5.41	12.25
MBHG	NP	NP	1.13	0.42	0.32	1.27	0.64	7.51	9.74	11.29
MFM2	NP	NP	1.16	3.47	0.37	1.47	1.83	9.85	13.52	18.15
MJC	NP	NP	1.89	1.07	0.22	1.17	1.72	5.66	8.77	11.73
THA	NP	NP	1.71	2.52	0.26	1.24	1.63	5.6	8.73	12.96
THB _PLOH	0.32	NP	1.76	1.61	0.3	1.33	1.53	3.36	6.52	10.21

NP=Not Present

Fuel Consumption

Unit	Shrub	Herb	Litter	Duff	1 hr	10 hr	100 hr	1000+ hr	Total Woody	Total
	Tons per acre									
AP018	1.17	0.34	0	NP	0.02	0.03	0	0	0.05	1.56
AP034	0.44	0.21	0	NP	0	0	0.01	0	0.01	0.66
AP050	1.99	0.34	0.08	NP	0.18	0.27	0.06	0	0.02	2.43
AP213	1.13	0.01	0.1	NP	0.01	0	0.01	0	0.11	1.35
AP312	2.58	0.13	0.28	NP	0.04	0.40	0.13	0	0.51	3.5
AP319	1.61	0.09	0.44	NP	0.08	0	0.03	0	0.57	2.71
AP320	2.31	0.21	0	NP	0.1	0	0.03	0.06	0.19	2.71
AP328	0.92	0.41	0	NP	0.05	0.13	0.05	0	0.23	1.56
E100BE	1.14	0.08	0	NP	0.08	0	0.04	0	0.12	1.34
E501B	1.17	0.11	0.56	NP	0.04	0	0.02	0	0.06	1.9
E505	0.15	0.03	0.91	NP	0.01	0	0	0	0.01	1.1
E807B	0.86	0.08	1.22	NP	0.05	0	0.03	0	0.08	2.24
E807D	1.37	0.02	1.44	NP	0.04	0	0.02	0	0.06	2.89
PH1V	4.11	0.02	0.55	NP	0.2	0.24	0	0	0.44	5.12
PH1V2	4.4	0.02	0.36	NP	0.2	0.3	0	0	0.5	5.28
PH2K	2.51	0.02	0.3	NP	0.08	0.02	0.06	0	0.16	2.99
S121	1.15	0.1	1.36	NP	0.04	0.13	0.01	0	0.18	2.79
S330	0.69	0.24	0	NP	0	0	0.07	0.15	0.22	1.15
DBBCLF	0	NP	1.66	0.44	0.2	0.81	0.77	1.34	3.12	5.22
DBCCLF	0	NP	0.67	0.05	0.05	0.15	0.36	0.93	1.49	2.21
DBWPLF	0	NP	1.51	0.4	0.15	0.56	0.68	1.22	2.61	4.52
DBWSLF	0.02	0	1.43	0.51	0.21	0.84	0.7	2.97	4.72	6.68
GWJCM	NP	NP	1.23	0.14	0.06	0.17	0.13	0.45	0.81	2.18
GWJJR	0.02	NP	2.21	0.23	0.07	0.38	0.23	0.13	0.81	3.27
MBHG	NP	NP	0.88	0.07	0.13	0.44	0.1	2.27	2.94	3.89
MFM2	NP	NP	0.94	0.73	0.41	1.28	0.67	1.66	4.02	5.69
MJC	NP	NP	1.48	0.52	0.13	0.46	0.35	0.54	1.48	3.48
THA	NP	NP	1.12	0.34	0.21	0.78	0.58	1.34	2.91	4.37
THB _PLOH	0.25	NP	1.38	0.18	0.18	0.64	0.5	0.87	2.19	4

NP=Not Present

Appendix 2: Eastern Fuel Consumption Spread Sheet Data Study Summary—JFSP Project # 08-1-6-01

Eastern fuel consumption study data spreadsheet for all data collected on the 29 units monitored. It includes study site descriptions and location, pre-fire environmental variables, fuel moisture content weather, and pre-fire loading and fuel consumption by fuelbed category.

This is in partial fulfillment of JFSP project # 08-1-6-01 and is being uploaded into the SEMIP repository and is posted on the Fire and Environmental Research Application Team's website: http://www.fs.fed.us/pnw/fera/

Attached to JFSP website: JFSP_08-1-6-01_ _consumption_dataset_app2.xlsx.

Attached to JFSP website: JFSP_08-1-6-01_consumption _dataset_documentation_app2.pdf

Appendix 3: Consumption Database Documentation—JFSP Project # 08-1-6-01

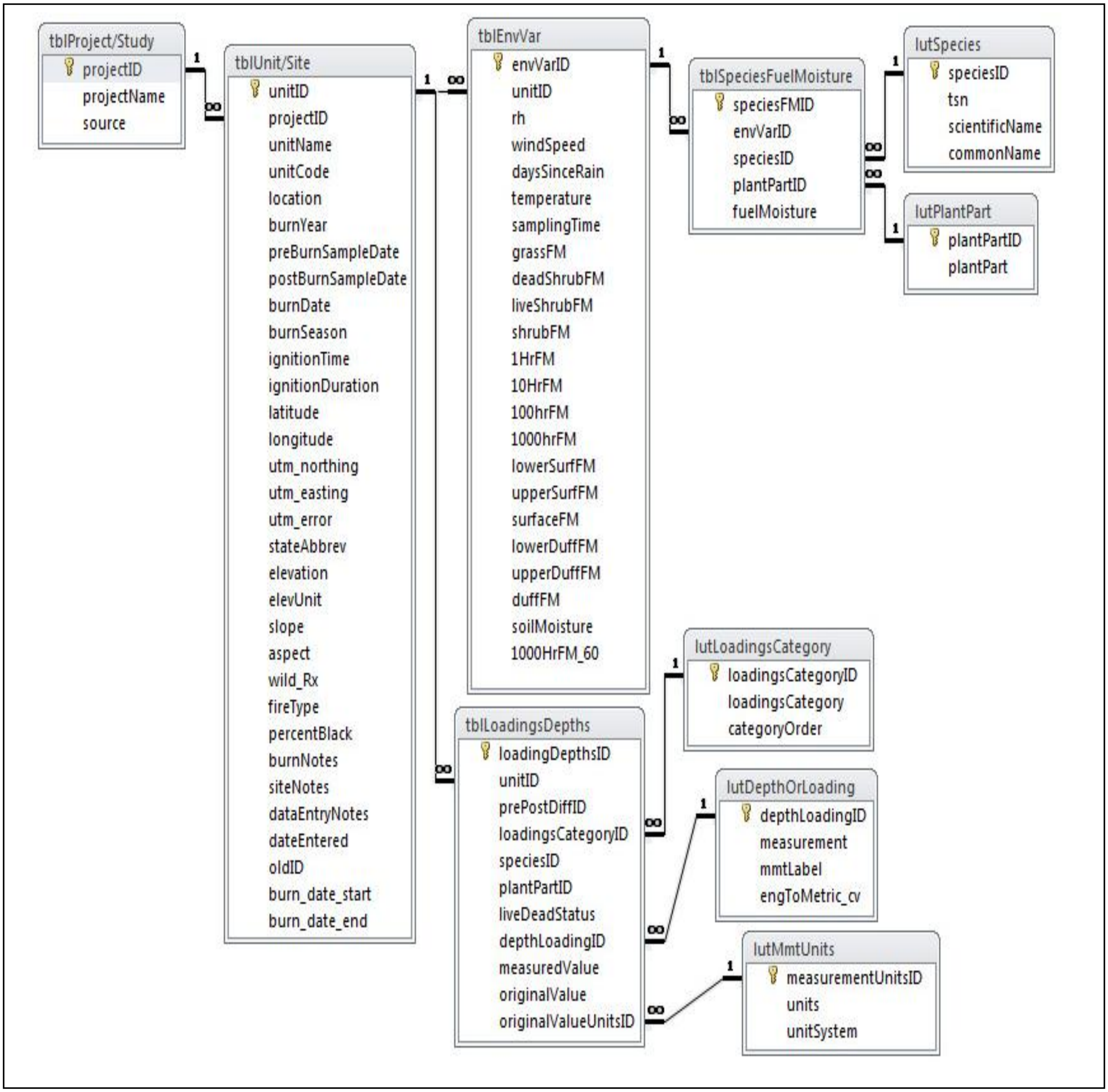
The FERA fuel consumption database was created to store internal and test consumption datasets on prescribed and wildfire burns. Over the past 30 years, FERA has conducted fuel consumption research in a variety of forest and shrubland types and under a range of prescriptions from broadcast burning of clearcut harvest units to prescribed burns in ponderosa pine and southern pine forests to boreal forest floor consumption in Alaska wildfires. The main objectives of creating the FERA database were to (1) house all of our existing datasets in a single repository with common variable names and units of measure, and (2) allow for additional datasets to be added, including test data from published research.

As part of a project to expand our understanding of fuel consumption in the eastern United States (this study, JFSP 08-1-6-01), we collected fuel consumption data (including pre- and post-burn fuel characteristics and day-of-burn environmental variables) for 29 burn units in the eastern United States. This dataset expands on FERA’s previous research in the southeastern United States (13 longleaf pine sites in Eglin AFB, 5 loblolly pine sites in Sumter AFB, and 31 flatwood shrub consumption sites throughout Florida). Consume 4.1 currently uses limited empirical models of woody fuel and forest floor consumption based on 18 southern pine sites. We plan to use this expanded dataset to improve our modeled fuel consumption for southern pine and mixed hardwood sites of the eastern United States. This is in partial fulfillment of JFSP project # 08-1-6-01 and is being uploaded in the SEMIP repository and is posted on the Fire and Environmental Research Application Team’s website: http://www.fs.fed.us/pnw/fera/. This data base is attached separately and named: JFSP_08-1-6-01_consumption_database_app3.mdb.

To provide a test dataset of our revised eastern fuel consumption models, we compiled independent fuel consumption data from other studies in the eastern United States. We contacted fire and fuels experts from a range of agencies and universities in the eastern United States to locate and review potential test datasets (see main text, table 1).

Attached to JFSP website: JFSP_08-1-6-01_consumption_database_app3.mdb

Attached to JFSP website: JFSP_08-1-6-01_consumption_database_documentation_app3.pdf


tblProject/Study
projectID
projectName
source
tblUnit/Site
unitID
projectID
unitName
unitCode
location
burnYear
preBurnSampleDate
postBurnSampleDate
burnDate
burnSeason
ignitionTime
ignitionDuration
latitude
longitude
utm_northing
utm_easting
utm_error
stateAbbrev
elevation
elevUnit
slope
aspect
wild_Rx
fireType
percentBlack
burnNotes
siteNotes
dataEntryNotes
dateEntered
oldID
burn_date_start
burn_date_end
tblEnvVar
envVarID
unitID
rh
windSpeed
daysSinceRain
temperature
samplingTime
grassFM
deadShrubFM
liveShrubFM
shrubFM
1HrFM
10HrFM
100hrFM
1000hrFM
lowerSurfFM
upperSurfFM
surfaceFM
lowerDuffFM
upperDuffFM
duffFM
soilMoisture
1000HrFM_60
tblSpeciesFuelMoisture
speciesFMID
envVarID
speciesID
plantPartID
fuelMoisture
lutSpecies
speciesID
tsn
scientificName
commonName
lutPlantPart
plantPartID
plantPart
tblLoadingsDepths
loadingDepthsID
unitID
prePostDiffID
loadingsCategoryID
speciesID
plantPartID
liveDeadStatus
depthLoadingID
measuredValue
originalValue
originalValueUnitsID
lutLoadingsCategory
loadingsCategoryID
loadingsCategory
categoryOrder
lutDepthOrLoading
depthLoadingID
measurement
mmtLabel
engToMetric_cv
lutMmtUnits
measurementUnitsID
units
unitSystem

Summary of the FERA Consumption Database

Project Name	**Data Source**	**No. Units**
ALASKA—		
Alaska forest floor consumption study (JFSP 03-3-1-08)	FERA	31
EASTERN—		
Midwest: Kentucky/Ohio 2009-2010 (JFSP 08-1-6-01)	FERA	5
MidWest: Kentucky/Virginia 2008-2009 (JFSP 08-1-6-01)	FERA	6
Eglin longleaf pine consumption study	FERA	13
Flatwoods fire seasonality study, Florida, 2009-2010 (JFSP 08-1-6-01; 09-1-01-2)	FERA	18
Flatwoods shrub consumption (JFSP 03-1-3-06)	FERA	31
Florida shrub consumption 2008-2009	FERA	8
Sumter loblolly pine consumption study	FERA	5
WESTERN—		
Western ponderosa pine consumption study	FERA	60
Sage shrubland consumption study	FERA	26
EASTERN TEST DATASETS—		
Clinton (test data)	Clinton et al. 1998	3
Kolaks (test data)	Kolaks et al. 2004	6
Loucks (test data)	Loucks 2005	10
Scholl & Waldrup (test data)	Scholl & Waldrup 2001	8
Sullivan (test data)	Sullivan etal 2003	12
Swift (test data)	Swift et al. 1993, Vose & Swank 1995	3

Shaded rows indicate data for the 29 units monitored for this study.

References

Clinton, B.D., Vose, J.M., Swank, W.T., Berg, E.C., and Loftis, D.L. 1998. Fuel consumption and fire characteristics during understory burning in a mixed white pine-hardwood stand in the southern Appalachians. USDA Forest Service Research Paper RP-SRS-12, Southern Research Station, Asheville, NC.

Kolaks, J. 2004. Fuel loading and fire behavior in the Missouri Ozarks of the central hardwood region. M.S. Thesis. University of Missouri - Columbia.

Loucks, E. 2005. The effects of landscape scale prescribed fire on fuel loading and tree health in an Appalachian hardwood forest, Kentucky. M.S. Thesis. University of Kentucky, Lexington, KY.

Scholl, E.R. and Waldrop, T.A. 2001. Photos for estimating fuel loading before and after Prescribeding in the Upper Coastal Plain of the Southeast. USDA Forest Service General Technical Report GTR-SRS-26, Southern Research Station, Asheville, NC.

Sullivan, B.T., Fettig, C.J., Otrosina, W.J., Dalusky, M.J., Berisford, C.W. 2003. Association between severity of Prescribeds and subsequent activity of conifer-infesting beetles in stands of longleaf pine. Forest Ecology and Management 185: 327-340

Swift, L.W., Jr., Elliott, K.J, Ottmar, R.D., and Vihnanek, R.E. 1993. Site preparation burning to improve southern Appalachian pine-hardwood stands: fire characteristics and soil erosion, moisture, and temperature. Can. J. For. Res. 23:2242-2254.

Vose, J. M. and W.T. Swank. 1993. Site preparation burning to improve southern Appalachian pine hardwood stands - Aboveground biomass, forest floor mass, and nitrogen and carbon pools. Canadian Journal of Forest Research 23(10): 2255-2262.

Wright, C.S. and Prichard, S.J. 2006. Predicting forest floor and woody fuel consumption from prescribed burns in ponderosa pine forests. Proceedings of the Fire Behavior and Fuels Conference, Nov. 13-17, San Diego, CA.

Wright, C.S. 2010. Effects of disturbance and fuelbed succession on spatial patterns of fuel, fire hazard, and carbon; and fuel consumption in shrub-dominated ecosystems. Ph.D. dissertation, University of Washington, Seattle, WA.

Database Variable Definitions

Project Database Table (tblProject)

Field Name	Field Type	Description
projectID	Long	Table unique recorder identifier/primary key
projectName	Text	Name of project
source	Text	Data source
unitID	Long	Table unique recorder identifier/primary key
projectID	Long	Links to tblProject.projectID
unitName	Text	
unitCode	Text	
burnYear	Long	
burnDate	Text	
burnSeason	Text	
burn_date_start	Date/Time	
burn_date_end	Date/Time	
preBurnSampleDate	Date/Time	
postBurnSampleDate	Date/Time	
ignitionTime	Long	hhmm using 24-hr clock
ignitionDuration	Text	Minutes
location	Text	Name of public land
stateAbbrev	Text	
latitude	Text	
longitude	Text	
utm_northing	Long	
utm_easting	Long	
utm_error	Long	
elevation	Long	
elevUnit	Text	
slope	Double	
aspect	Text	
wild_Rx	Text	Prescribed burn or wild fire
fireType	Text	Back, head, flank, upslope, etc.
percentBlack	Text	
burnNotes	Memo	
siteNotes	Memo	
dataEntryNotes	Memo	

Database Table (tblUnit)

Field Name	Field Type	Description
envVarID	Long	Table unique recorder identifier/primary key
unitID	Long	Links to tblUnit.unitID
daysSinceRain	Long	Days since rain (>2.5 mm)
rh	Double	Relative humidity %
windSpeed	Double	Midflame windspeed, kph (= 1.609344 * mph)
temperature	Double	Temperature
shrubFM	Double	% Fuel moisture of shrub foliage
deadShrubFM	Double	%, Fuel moisture of dead shrub foliage
liveShrubFM	Double	%, Fuel moisture of live shrub foliage
grassFM	Double	%, Fuel moisture of grasses
1HrFM	Double	% Fuel moisture of > 1/4 inch woody fuels
10HrFM	Double	% Fuel moisture of 1/4 to 1 inch woody fuels
100hrFM	Double	% Fuel moisture of 1 to 3 inch woody fuels
1000hrFM	Double	% Fuel moisture of 3 to 9 inch woody fuels
surfaceFM	Double	Fuel moisture % of surface material (litter)
lowerSurfFM	Double	Lower surface material moisture %
upperSurfFM	Double	Upper surface material moisture %
duffFM	Double	Duff fuel moisture %
lowerDuffFM	Double	Lower duff moisture %
upperDuffFM	Double	Upper duff moisture %
soilMoisture	Double	%, Moisture content of mineral soil
samplingTime	Text	Burn initiation, mid burn, or end of burn

Fuel Moisture Database Table (tblFuelMoisture)

Field Name	Field Type	Description
speciesFMID	Long	Table unique recorder identifier/primary key
envVarID	Long	Links to tblEnvVar.envVarID
speciesID	Long	Links to lutSpecies.speciesID
plantPartID	Long	Stem, rachis, foliage. Populated only if certain part of plant was sampled.
fuelMoisture	Double	%

Other Tables

Table	Field Name	Field Type	Description
tblFuelMoisture	speciesFMID	Long	Table unique recorder identifier/primary key
	envVarID	Long	Links to tblEnvVar.envVarID
	speciesID	Long	Links to lutSpecies.speciesID
	plantPartID	Long	Stem, rachis, foliage. Populated only if certain part of plant was sampled.
	fuelMoisture	Double	%
tblLoadingsDepths	loadingDepthsID	Long	Table unique recorder identifier/primary key
	unitID	Long	Links to tblUnit.unitID
	prePostDiffID	Long	1 = preburn measurement, 2 = post, 3 = consumed
	loadingsCategoryID	Long	Grass, shrub, forb, 1-hr, etc. Links to lutLoadingsCategory.loadingsCategoryID
	speciesID	Long	Only if appl. Null if measurement applies to all spp. Links to lutSpecies.speciesID
	plantPartID	Long	Only if appl. Null if measurement applies to whole plant. Links to lutplantPart.plantPartID
	liveDeadStatus	Text	If appl. If null, assume live/dead together
	depthLoadingID	Long	1 = depth, 2 = loading
	measuredValue	Double	Either cm (depth) or Mg/ha (loading)
	originalValue	Double	Value before conversion to metric
	originalValueUnitsID	Long	tons/ac, lbs/ac, inches, etc. Links to lutMmtUnits.measurementUnitsID
lutDepthOrLoading	depthLoadingID	Long	Table unique recorder identifier/primary key
	measurement	Text	Depth or loading
	mmtLabel	Text	
	engToMetric_cv	Double	Multiply if eng, divide if metric
lutLoadingsCategory	loadingsCategoryID	Long	Table unique recorder identifier/primary key
	loadingsCategory	Text	Shrub, 1-HR, Surface Material, etc.
	categoryOrder	Long	
lutMmtUnits	measurementUnitsID	Long	Table unique recorder identifier/primary key
	units	Text	
	unitSystem	Long	1 = English, 2 = metric
lutPlantPart	plantPartID	Long	Table unique recorder identifier/primary key
	plantPart	Text	leaf, stem, leaf+stem, etc.
lutSpecies	speciesID	Long	Table unique recorder identifier/primary key
	tsn	Long	Taxonomic serial number from ITIS database
	scientificName	Text	
	commonName	Text	

Appendix 4: Radiant Emission Spectra Data Study Summary—JFSP Project # 08-1-6-01

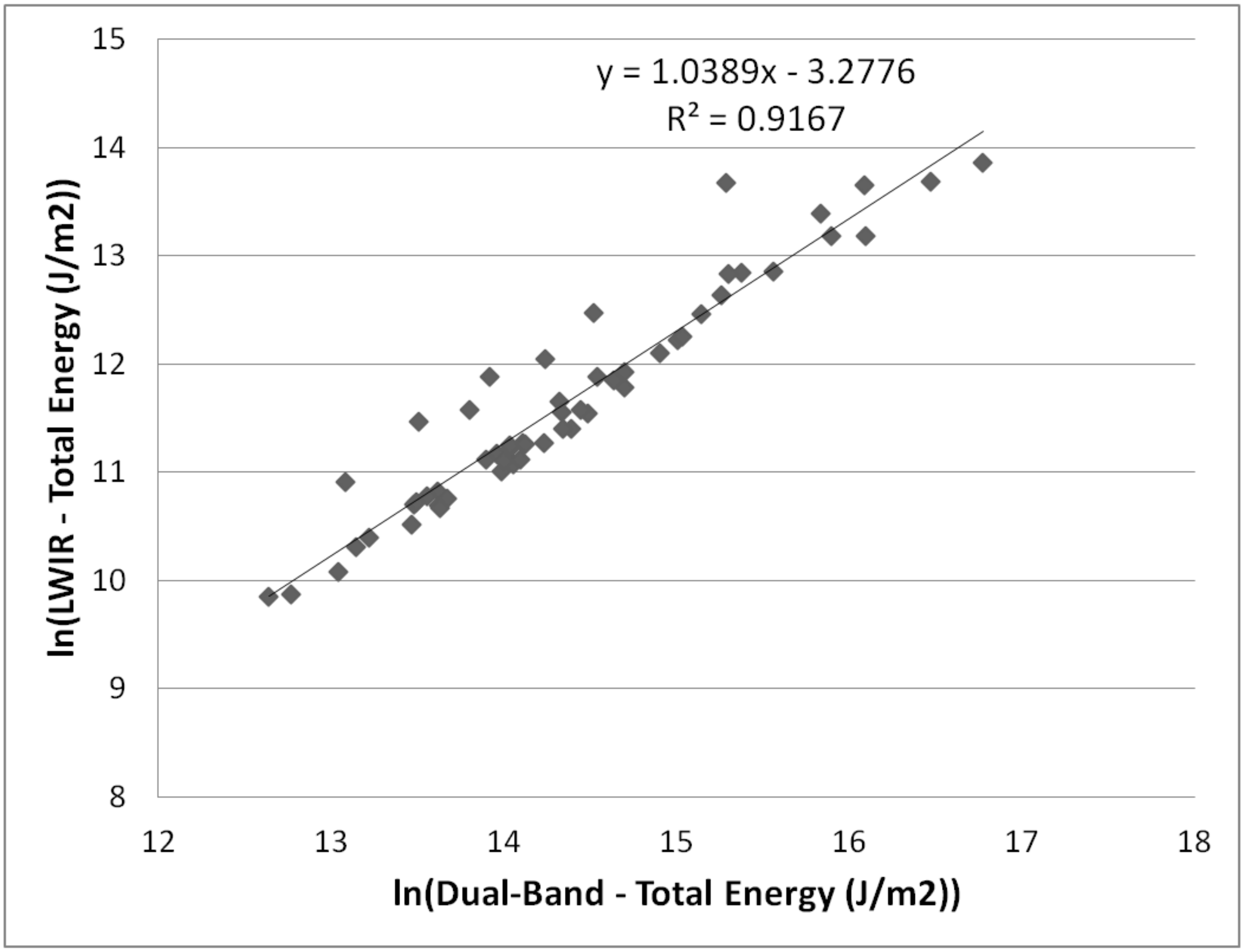
List of ground-calibration datasets, summarized to total ground-leaving energy from the fires. Included are total energy calculated from dual-band radiometry (Kremens et al. 2010) and from the restricted bandpass LWIR detectors as described by Kremens and Dickinson (in review, Appendix 5). The plot indicates that the physics-based simulation approach as discussed in the in Kremens and Dickinson (in review, Appendix 5) has validity, relating the well-understood dual-band method of estimating energy to energy inferred from a detector with a single, limited bandpass. The next step is to validate the calibration approach with ground-based data.

Kremens, R.L.; Smith, A.M.; Dickinson, M.B. 2010. Fire Metrology: Current and future directions in physics-based measurements., Fire Ecology, 6, pp. 13-35.

Kremens, R.L.; Dickinson, M.B. (in review) Flame-font scale numerical simulation of wildland fire radiant emission spectra as an aid to observation of wildfires.

Attached to JFSP website: JFSP_08-1-6-01_grooound_consumption_calibration_dataset_app4.pdf

File	Total Energy (J/m^2)		LN(Total Energy)	
	Dual-band radiometer	LWIR detector	Dual-band radiometer	LWIR detector
BearWaller_Plot1_IR_30April2007.xlsm	9750005.8	848028.6	16.1	13.7
BearWaller_Plot2_IR_30April2007.xlsm	4231336.2	305080.0	15.3	12.6
BearWaller_Plot3_IR_30April2007.xlsm	4779853.2	375082.1	15.4	12.8
BearWaller_ExtraPlot4_IR_30April2007.xlsm	4374764.4	860678.6	15.3	13.7
BearWaller_BatRoost_IR_30April2007.xlsm	14253997.1	875964.3	16.5	13.7
PowderMill_Plot1_IR_10April2007.xlsm	1666992.3	113912.9	14.3	11.6
PowderMill_Plot3_IR_10April2007.xlsm	2975629.5	179597.9	14.9	12.1
PowderMill_Plot8_IR_10April2007.xlsm	9801704.7	525435.7	16.1	13.2
PowderMill_Plot9_IR_10April2007.xlsm	3774429.1	256198.6	15.1	12.5
TarHollow_Plot1_IR_20April2007.xlsm	5732727.3	378535.7	15.6	12.8
TarHollow_Plot4_IR_20April2007.xlsm	19279550.6	1044375.0	16.8	13.9
TarHollow_Plot6_IR_20April2007.xlsm	7539825.7	653346.4	15.8	13.4
TarHollow_PlotEXTRA1_IR_20April2007.xlsm	8013919.7	528264.3	15.9	13.2
608A_Plot3_IR_Calibrated_1March2008.xlsm	1159348.3	71093.6	14.0	11.2
608A_Plot4_IR_Calibrated_1March2008.xlsm	2072675.2	144597.5	14.5	11.9
307B_Plot2_IR_Calibrated_2March2008.xlsm	820351.0	49687.5	13.6	10.8
307B_Plot4_IR_Calibated_2March2008.xlsm	715462.1	44216.1	13.5	10.7
307B_Plot5_IR_Calibrated_2March2008.xlsm	553186.6	32715.7	13.2	10.4
HomeField_Plot1_IR_Calibrated_3March2008.xlsm	1347139.3	77894.3	14.1	11.3
HomeField_Plot2_IR_Calibrated_3March2008.xlsm	1089616.8	66630.4	13.9	11.1
NorthBoundary_Plot1_IR_Calibrated_5March2008.xlsm	708340.4	36860.0	13.5	10.5
NorthBoundary_Plot2_IR_Calibrated_5March2008.xlsm	510435.7	29741.4	13.1	10.3
NorthBoundary_Plot3_IR_Calibrated_5March2008.xlsm	309063.0	18948.6	12.6	9.8
JohnBaptist_Plot1_IR_6March2008.xlsm	726935.5	45050.0	13.5	10.7
JohnBaptist_Plot2_IR_6March2008.xlsm	824697.3	43781.4	13.6	10.7
WolfPen_Plot20_IR_7April2008.xlsm	1776588.2	89275.0	14.4	11.4
WolfPen_Plot24_IR_7April2008.xlsm	1363290.7	77212.1	14.1	11.3
WolfPen_Plot25_IR_7April2008.xlsm	1683360.2	103174.3	14.3	11.5
WolfPen_Plot27_IR_7April2008.xlsm	350707.5	19252.1	12.8	9.9
BuckCreek_Plot2_IR_Calibrated_17April2009.xlsm	1245800.8	73808.6	14.0	11.2
EglinAFB_907D_Plot1_IR_Calibrated_9Jan2010.xlsm	462856.0	23585.0	13.0	10.1
EglinAFB_601_Plot1_IR_Calibrated_10Jan2010.xlsm	1700008.7	88552.1	14.3	11.4
EglinAFB_601_Plot2_IR_Calibrated_10Jan2010.xlsm	1272454.7	63953.6	14.1	11.1
EglinAFB_702D_Plot1_IR_Calibrated_11Jan2010.xlsm	1322165.9	66635.0	14.1	11.1
EglinAFB_702D_Plot2_IR_Calibrated_11Jan2010.xlsm	770082.7	47793.9	13.6	10.8
EglinAFB_702D_Plot3_IR_Calibrated_11Jan2010.xlsm	1186833.0	60295.0	14.0	11.0
EglinAFB_702D_Plot4_IR_Calibrated_11Jan2010.xlsm	869362.7	46510.0	13.7	10.7
EglinAFB_100B_Plot1_IR_Calibrated_12Jan2010.xlsm	1520516.4	77977.1	14.2	11.3
EglinAFB_100B_Plot2_IR_Calibrated_12Jan2010.xlsm	1952033.4	103037.9	14.5	11.5
EglinAFB_100B_Plot3_IR_Calibrated_12Jan2010.xlsm	1245268.1	76635.0	14.0	11.2
EglinAFB_100B_Plot4_IR_Calibrated_12Jan2010.xlsm	834889.4	42905.7	13.6	10.7
DATA_MACA_FloatingMill_Plot1_IR_Calibrated.xlsm	1528637.5	169460.4	14.2	12.0
DATA_MACA_FloatingMill_Plot2_IR_Calibrated.xlsm	1106815.0	144224.2	13.9	11.9
DATA_MACA_FloatingMill_Plot3_IR_Calibrated.xlsm	2422727.9	130471.1	14.7	11.8
DATA_MACA_FloatingMill_Plot4_IR_calibrated.xlsm	1206473.0	66240.0	14.0	11.1
MACA_JoppaChurch_Plot1_IR_Calibrated.xlsm	734259.7	94520.0	13.5	11.5
MACA_JoppaChurch_Plot2_IR_Calibrated.xlsm	1885794.5	105543.6	14.4	11.6
MACA_JoppaChurch_Plot3_IR_Calibrated.xlsm	987210.2	105892.9	13.8	11.6
MACA_JoppaChurch_Plot4_IR_Calibrated.xlsm	2415214.6	150776.4	14.7	11.9
TarHollow_Ailanthus_UnitA_Plot1_IR_Calibrated.xlsm	3285431.0	202397.1	15.0	12.2
TarHollow_Ailanthus_UnitA_Plot2_IR_Calibrated.xlsm	480781.9	54263.6	13.1	10.9
TarHollow_Ailanthus_UnitB_Plot1_IR_Calibrated.xlsm	4425545.5	371187.9	15.3	12.8
TarHollow_Ailanthus_UnitB_Plot2_IR_Calibrated.xlsm	2025604.7	258567.9	14.5	12.5
Acorn_Hill_Plot1.xlsm	2279094.4	138841.8	14.6	11.8
Acorn_Hill_Plot2.xlsm	3397824.5	208292.5	15.0	12.2


y = 1.0389x - 3.2776
R² = 0.9167
ln(LWIR - Total Energy (J/m2))
ln(Dual-Band - Total Energy (J/m2))
15
14
13
12
11
10
9
8
12
13
14
15
16
17
18

Appendix 5

Kemens, Robert L.; Dickinson, Matthew B. Flame-front scale numerical simulation of wildland fire radiant emission spectra as an aid to observation of wildland fire. Draft manuscript for submission to International Journal of Wildland Fire; in partial fulfillment of JFSP Project Number 08-1-6-01.

Attached to JFSP website: JFSP_08-1-6-01_kremens_draft_manuscript.pdf

Flame-front scale numerical simulation of wildland fire radiant emission spectra as an aid to observation of wildland fires

Robert L. Kremens, Rochester Institute of Technology, Rochester, NY

Matthew B. Dickinson, US Forest Service, Delaware, OH

For submission to International Journal of Wildland Fire

Abstract

We have simulated the radiant emission spectra from wildland fires such as would be observed at a scale encompassing the pre-frontal fuel bed, the flaming front, and the zone of post-frontal combustion and cooling. These "mixed-pixel" simulations were developed using a combination of first principle radiant emission physics and experimental information on the temperature and emissivity of the pre- and post-frontal background and flaming zone. We simulate the spectra as the sum of N blackbody spectra from N areas of randomly chosen areal fraction, emissivity, and temperature. We neglect the contribution to the spectrum from emission lines of water, carbon dioxide and other combustion products, as these emissions will be absorbed strongly in the atmosphere between the fire and the remote sensing platform. We are particularly interested in overhead observations because much of our previous work at landscape scale has been performed using low-flying aircraft and long-wave infrared (8 μm - 12 μm) camera systems and associated ground-based sensors. We observed from these simulations (N = 10,000) that there is a well-behaved functional relationship that relates ground-leaving to sensor-reaching power (W m^{-2}). The ability to assume an observed spectral shape greatly simplifies the use of any overhead or remote measurement system. Error decreases asymptotically as the number of fractional areas increases (we show results for spectra summed over 30 areal fractions) and power increases log-linearly with the single blackbody temperature. Error is highest for detectors that do not sample in the mid-wave portion of the infrared spectrum (~3 μm -5 μm) where the emitted power density is the highest for ~1000K fire sources. We will discuss the implications of this result for satellite, aircraft and ground-based measurements of fire radiant power density.

Introduction

In most areas of remote sensing, the emission, transmission and reflection characteristics of the target are well known, either through laboratory or field measurements or, ideally, a combination of both. Emission, transmission and reflection are often known as a function of wavelength which allows wavelength-specific methods to be used to identify and quantify remotely sensed targets. These facts are in stark contrast to remote observation of wildland fires, where very few measurements have been made of the emission spectra, emissivity, angular distribution, or any other physical parameters of interest to remote sensing observers. Confounding fire observations further is the fact that most observed fire ground sample areas, even at high resolution, are 'mixed pixels', a combination of flames, and non-flaming background of a range of temperatures. Wildland fires have been observed from airborne and satellite remote sensing platforms for decades (references). These observations have often been made in the long wave infrared portion of the electromagnetic spectrum (LWIR, 8 μm – 12 μm) for several reasons:

1. Wildland fire events emit strongly in this region,
2. There is little interference in the LWIR from reflected solar illumination, especially for fires which are highly emissive 'hot' targets,
3. Atmospheric transmission of LWIR is high, and
4. The technology and methods for observation in this band are well developed.

A remote sensing detector is sensitive to radiation in a spectral pass band that is defined by the detector spectral response, transmission of the various optical elements, and transmission of the atmosphere that intervenes between the ground and the atmosphere. The governing equation for detection is:

(1)

where S is the signal generated by a detector, $R(\lambda)$ is the spectral responsivity of the detector, $T_a(\lambda)$ is the atmospheric transmission from the source to the detector, $T_o(\lambda)$ is the transmission of the optics in the system, $M(\lambda)$ is the spectral radiance of the source and G is a geometric factor relating lens area and other geometric factors to the received signal, and the integral is over all wavelengths. Using a well-characterized detector of limited bandwidth observing a 'mixed fire pixel' as defined above and without any other information, it is impossible to know the total surface-leaving power density of the target from the received signal alone because of the dependence on the spectral characteristics of the source and the effects of the intervening atmosphere. If the goal of remote sensing observations of wildland fire is to know not only the position of the fire but the emissive power and energy density, then we require additional information about the spectra, areal fractions of the mixed components and other radiative properties (emissivity, reflectivity and transmission). This additional information may be obtained by using more than one spectral bands (e.g., Kremens *et al.* 2010, Riggan *et al.* 2004, Daniels 2007). Mathematically, the problem of finding the emissive power density from a remote source given only the output of a restricted bandwidth detector is said to be an 'under-constrained inverse problem'.

An example of the preceding problem is shown in Figure 1. In this example, two blackbodies emit radiation according to the Boltzmann radiation law. One source has a temperature of 1300K and an emissivity of 0.09. The other source has a temperature of 500K and an emissivity of 0.8. These examples represent a fire and warm background after the passage of the fire. The power received by a detector with a bandwidth of 8 μm -12 μm for both spectra is the same, even though the hot source has more than 5 times as much total power output as the cool source. Using a detector with limited bandwidth and no other information about the spectral signature of the source, it is not possible to uniquely determine the total power emitted by the source.

The radiation from a fire originates from several sources; blackbody emission from incandescent soot within the flame bag and potentially strong band emission from hot water vapor, unburned hydrocarbons, CO and CO_2 produced during the combustion process. The emission from CO_2 and water vapor are strongly absorbed by the intervening atmosphere, leaving the blackbody radiation from the fire in the LWIR and other high-transmission regions as the primary observable radiation for a distant observer (Schott 1997, p.84). The soil and plant matter around the flames may also be heated by the fire and will also emit as a blackbody with a temperature lower than that of the fire. Atmospheric transmission is well understood (Schott 1997 pp. 74-85), at least where smoke is not too thick, and we assume for the purposes of this paper that atmospheric effects on the spectral characteristics of the radiation that reaches the detector can be quantified. Our primary goal for this work, therefore, is to simulate a wildland fire ground sample area as would be seen by a remote sensing detector, and to derive spectral properties for this area that will allow unique determination of the emitted flux density using a detector of limited spectral bandwidth.

Methods

We formulated a computer simulation model (Figure 2) using the Python language and various adjunct Python libraries (SciPy, matPlotlib. pyplot, and csv). The model developed for these simulations uses the following assumptions:

1. A fire ground sample area consists of multiple emitting surfaces or volumes each with a different temperature, emissivity and fractional area (Figure 3).
2. The maximum temperature of a wildland fire flame is approximately 1300K and the minimum temperature about 1000K (measured using thermocouples in laboratory

experiments [Bret Butler, private communication] and through our own observations using dual band radiometers (unpublished); see also Martin et al. 1969).

3. The emissivity of a fire can vary from 0.05 (thin flames in the direction of observation) to as high as 0.5. (~3 m or more flame depth, Pastor *et al*. 2002 and our unpublished observations) The emissivity of the warm soil background can vary between 0.6 and 0.85 (Kremens *et al.*, 2003)
4. The spectral flux density and spectral power density from a 'mixed' ground sample area may be obtained by superposition of the spectral emissions from the multiple emitting surfaces.
5. The radiation from the ground sample area is distributed uniformly in space ('Lambertian radiator' assumption)

In each simulation of a fire pixel, we generated a spectrum by summation of N (N = 2-30) blackbody spectra, each with a randomly selected emissivity (subject to the constraints above), randomly selected temperature (again subject to the constraints above) and randomly selected areal fractions (where the areal fractions sum to 1, the total area in the field of view of the detector). We repeated this process 10,000 times, to represent an ensemble of possible areal fractions, temperatures and emissivities from the ground sample area. From previous manual simulations, we believed that the summation obtained by the above process would be very nearly identical in spectral form to a Boltzmann spectral distribution from a single temperature material. Because of the highly nonlinear functional dependence of the total emissive power on the temperature, we hypothesized that the overall spectral shape from such a summation should be dominated by the highest temperature (flaming) components. To test this hypothesis, we fit a Boltzmann distribution with a *single* temperature to the summed spectra using a non-linear curve fit method. We examined the goodness-of-fit of this single temperature distribution using conventional metrics and also compared the power and energy densities from numerical integration of both the fit and the 'true' data from the multi-object simulation. The fit parameters are the temperature (which controls the width and peak location of the distribution) and the emissivity-fractional area product (which control the 'height' of the distribution, see Kremens 2010).

In addition the summed spectra over the infrared region, we calculated the received detector power for several different restricted bandwidth detector systems as defined in Table 1. These systems have responses that are typical of commercially available single- and multiple-detector arrays that would be used for observation of wildland fire. Note that the 'WASP' detector in Table 1 corresponds to the airborne sensor system designed and built at the Rochester Institute of Technology for observation of wildland fire events. This system has been deployed nearly 30 times to create time-sequence observations of wild and prescribed fires (Ononye, *et al.* 2005). With results of the simulations, we parameterize a statistical model by relating total power to sensor-reaching power density. Standard laboratory calibration procedures are then used to relate sensor-reaching power density to raw response of a restricted bandpass detector (digital number, DN; Palmer and Grant 2010; Figure 4). Thus, we demonstrate how a measurement of only the digital signal from a restricted bandwidth detector can be used to derive a direct measure of ground-leaving power density.

Results

Graphical examples of the single-temperature fit applied to the sum spectra are shown in Figure 5 while mean and range of the pixel temperature and εA product of the blackbody (Boltzman) spectra that best fit simulated pixels are given in Table 2. Total power of the summed spectra was closely related to power derived from the best fit blackbody pixel temperature (total power = 448 + 0.999 x blackbody power; RMSE = 103 W m^{-2}).

Log-transformation of total power resulted in linear regression relationships with log-transformed sensor-reaching power (e.g., Figure 7). Variance distributions were relatively homogeneous across the range in sensor-reaching power. The linear regression parameters and associated correction factors for back-transformation are given in Table 1. RMSE for back-transformed total power ranged over roughly four orders of magnitude (~0.1 to 1000 W m^{-2}) with RMSE's of <1 to 8% of mean total power. Correction factors were correspondingly small, ranging from unity to 1.02. The greatest error was for detectors whose passband was restricted to the longwave portion of the infrared spectrum (Figure 6).

Discussion

The primary motivation for this work was to determine if it were possible to estimate, with reasonable error, the ground leaving radiant flux from a wildland fire given only an observation in a restricted bandwidth. Using our simulations, we have derived relationships between the signal from common restricted bandwidth detectors and ground leaving radiant power from a fire that will be useful for future observations and also for design of future airborne fire observation platforms. Our simulations (Figure 7 and Table 1) suggest that the relationship between total power and detected power will be log-linear across a range of detectors. The close relationship between total power calculated directly from the summed spectra and blackbody power (estimated from the blackbody temperature that best describes the summed spectra from each mixed-temperature pixel) reflects dominance of pixel radiation by active combustion. This relationship provides a potential means of using fire model output to simulate remotely-sensed wildland fire scenes.

Error arising from the model fit between total emissive power of the summed spectra and sensor-reaching power in a restricted bandpass is highest where the detector bandpass does not include the mid-wave (Figure 6). This is because at the average temperature of a simulated pixel (determined in our simulations to be ~ 1000K, Table 2) the Boltzmann distribution peaks in the 3 μm wavelength range. The increase in error can be seen in examples from the WASP (8 μm – 9.2 μm) longwave detector and a KBr (0.1 μm – 30 μm) detector (Figure 6). In a following paper, we will validate the proportionality relationships determined in this study against field data from dual-band radiometers from which we can estimate total fire radiated power flux density. We have extensive data from these sensors both from 'field scale' (~100 m^2) controlled experiments and prescribed fires.

Conclusions

Using a numerical simulation we have been able to determine functional relationships between sensor-reaching flux density and surface-leaving flux density for mixed-temperature pixels characteristic of areas in and around wildland fire flaming fronts. The simulations appear to be very general, covering a wide range of spatial and fire behavior parameters, and should be definable for any infrared sensor. Ignoring atmospheric interception of fire radiation, error in total power predictions resulting from these relationships will be least for sensors that detect in the midwave region. However, our simulations suggest that error will be no greater than 8% of total power even for longwave detectors. These results are only possible, it appears, because power emanating from wildland fire pixels is dominated by high temperature combustion. For the example of the RIT 'WASP' airborne sensor system the equation relating fire radiated power and sensor-received power is:

(2)

Where P_t is the total radiated fire power and P_{WASP} is the calibrated, sensor-reaching power.

References

Daniels, A. 2007. Field guide to infrared systems. SPIE Publishing, Bellingham, Washington, USA.

Martin, R. E., Cushwa, C. T., and Miller, R. L. (1969). Fire as a physical factor in wildland management. In "Proceedings of the Ninth Annual Tall Timbers Fires Ecology Conference," pp. 271-288. Tall Timbers Research Station, Tallahassee.

Kremens, R.L.; Smith, A.M.; Dickinson, M.B. 2010. Fire Metrology: Current and future directions in physics-based measurements., *Fire Ecology, 6, pp. 13-35*.

Kremens, R., Faulring, J., Hardy, C. 2003. Measurement of the time-temperature and emissivity history of the burn scar for remote sensing applications, published in the proceedings of the 2nd Fire Ecology Congress (American Meteorological Society) Orlando Fl, November 2003.

Ononye, A., A. Vodacek, Y. Li, and Z. Wang. 2005. Mapping of active fire area by image gradient technique using multi-spectral imagery. In: Remote Sensing for Field Users. Proc. 10th Biennial USDA Forest Service Remote Sensing Applications Conference. Salt Lake City, UT. CD-ROM, ISBN 1-57083-075-4, ASPRS

Palmer, J.M. and Grant B.G. 2010. The Art of Radiometry. (Chapter 7) SPIE Press, WA, USA

Pastor, E., A. Rigueiro, L. Zárate, A. Giménez, J. Arnaldos & E. Planas. 2001. Experimental methodology for characterizing flame emissivity of small scale forest fires using infrared thermography techniques. Forest Fire Research & Wildland Fire Safety, Viegas (ed.)/ Millpress, Rotterdam, ISBN 90-77017-72-01

Riggan PJ, Tissell RG, Lockwood RN, Brass JA, Pereira JAR, Miranda HS, Miranda AC, Campos T, Higgins R. 2004. Remote measurement of energy and carbon flux from wildfires in Brazil. Ecological Applications 14, 855-872. doi: 10.1890/02-5162.

Schott, J.R. 1997. Remote Sensing, the Image Chain Approach. Oxford University Press, NY, USA.

Sprugel, D. G. 1983. Correcting for bias in log-transformed allometric equations. Ecology 64:209-210.

Tables

Table 1 - Regression parameters, correction factors, and fit between total power (Pt, W m^{-2}) and power measured by a range of detectors. The detectors represent the bulk of commercially available detector systems (imaging and point detectors). The CaF_2, LWPSi, KBr, and Sapphire detector spectral characteristics represent commonly used windows for thermopile detectors. Power cutoff points (50%) describe spectral response. No correction for atmospheric absorption is included in these relationships. All results are based on 10,000 random fire pixels with 30 fractional areas. Regression parameters are from log-transformed total power predicted from log-transformed sensor-reaching power. The correction factor (CF) is a multiplier to back-transformed total power (Sprugel 1983). The table is sorted by RMSE.

	Cutoff (µm)		**Power (W m^{-2})**			**Regression results**			
Detector	**Lower**	**Upper**	**Mean**	**Min**	**Max**	Intercept	Slope	CF	RMSE
KBr	0.1	30.0	12679	4004	31554	0.0002	1.000	1.0000	0.09
CaF2	0.1	12.5	12071	3608	30520	0.3186	0.971	1.0000	41.04
Sapphire	0.1	6.5	9937	2491	26362	1.2087	0.896	1.0005	176.17
MW	3.0	5.0	4298	1202	10643	1.3413	0.969	1.0006	210.72
LWPSi	5.0	20.0	4276	1879	8606	-1.6556	1.327	1.0086	793.55
WASP	8.0	9.2	447	204	868	0.9518	1.390	1.0122	943.47
LW	8.0	12.0	1237	599	2324	-1.0388	1.471	1.0151	1044.33

Table 2 - Summary output derived from the simulations. Total power is summed power over each ground sampling area (pixel, Figure 2) obtained by summation of the blackbody spectral emissions from all aerial fractions (Figure 4). A non-linear curve fit procedure was used to determine the pixel temperature and emissivity-area product that best reproduced the summed spectrum (Figure 5).

Variable	**Mean**	**Min**	**Max**
Total power (W m^{-2})	12679	4004	31554
Fit temperature (K)	1079	821	1225
Fit emissivity area product (dimensionless)	0.16	0.06	0.27

Figures

Figure 1 - Radiation as observed in a limited spectral bandwidth from two sources of different temperatures and emissivity. The total radiance emitted from the high temperature source (dashed line) is about 5 times larger than the radiance from the low temperature source, even though the radiance observed in a typical 'long wave infrared' (8-12mm) detector is the same.

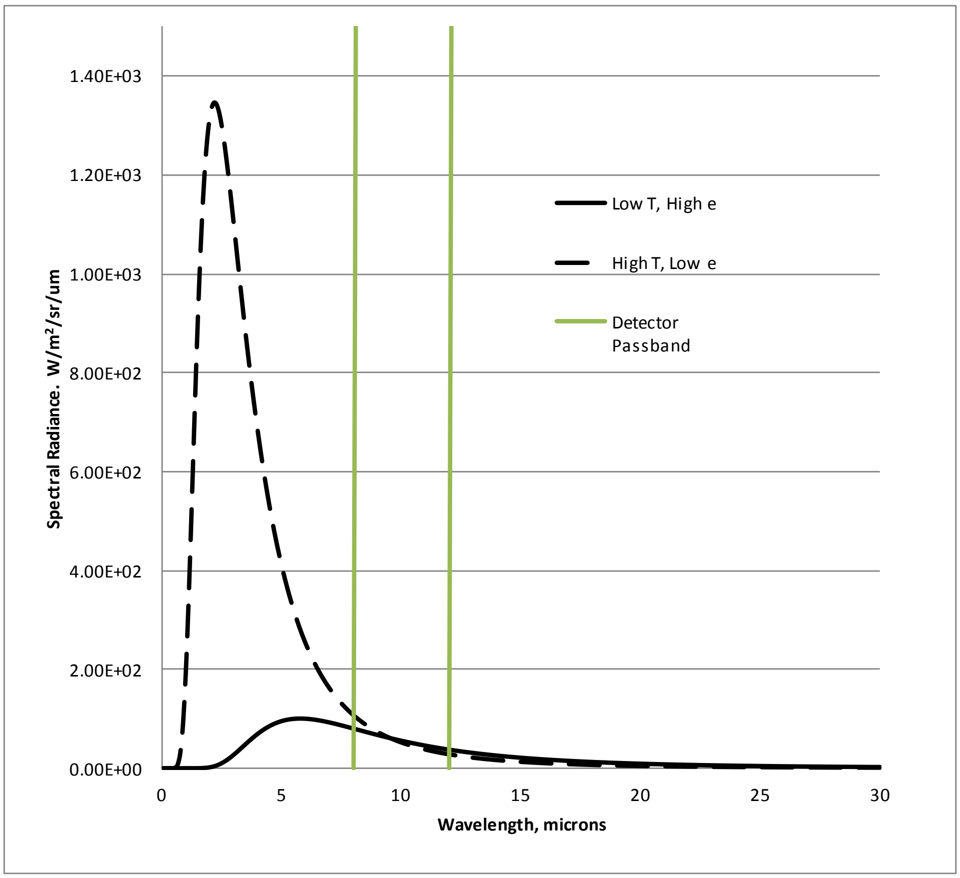


Figure 2 - Schematic representation of the simulation process showing in this case N=4 different emitting components in the ground sample area. For our simulations we used between 2 and 30 different sub-components of the ground sample area to simulate fire scenes of varying complexity, and to determine if there were any effects of sub-area complexity on the fit temperature or quality of fit using a single-temperature distribution.

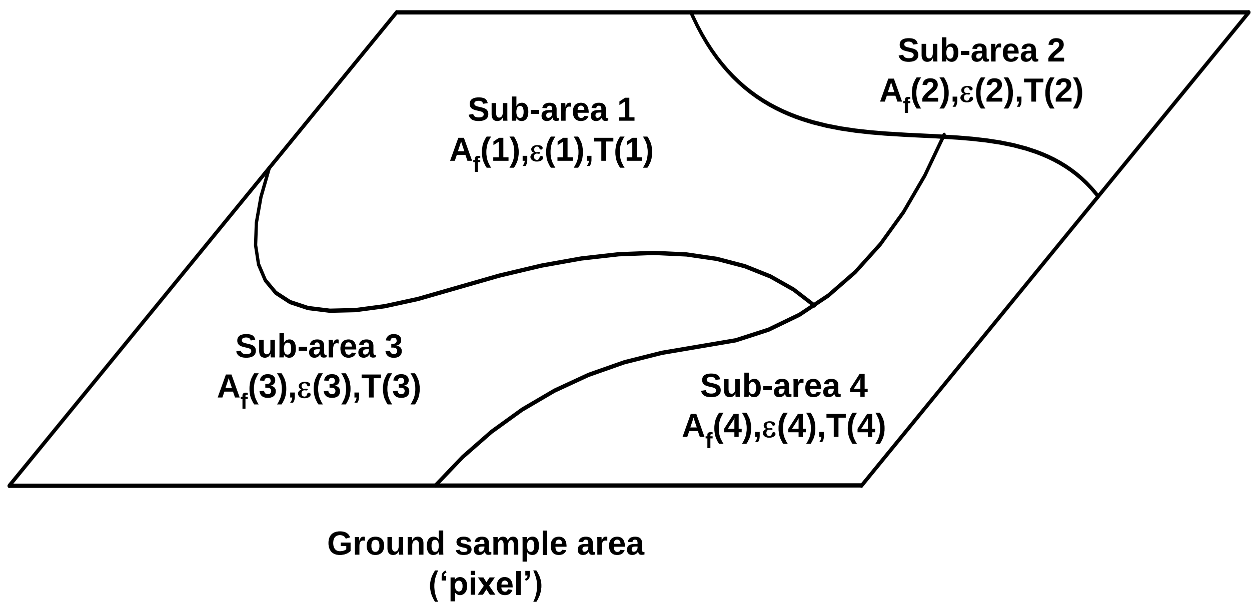
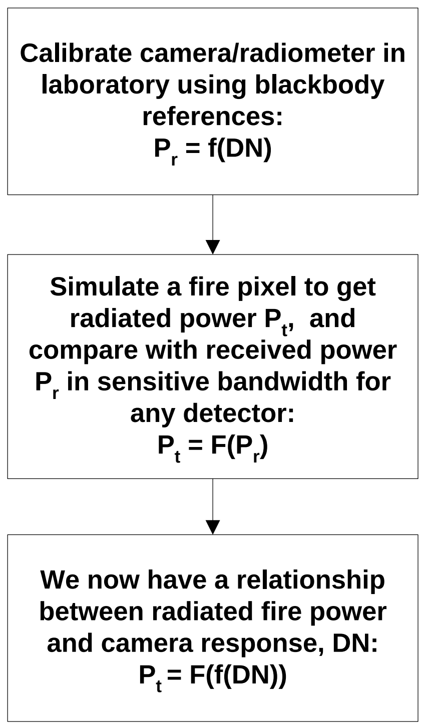


Figure 3 - Using these simulations and laboratory measurements to observe wildland fire using a restricted bandwidth detector. P_r = power received by the detector in its sensitive bandpass and P_t is the total power radiated by the fire, DN is the raw digital count from the sensor (pre-corrected for offset and nonlinearities, if necessary).



_

Figure 4 - Flow chart showing the major steps in the simulation.

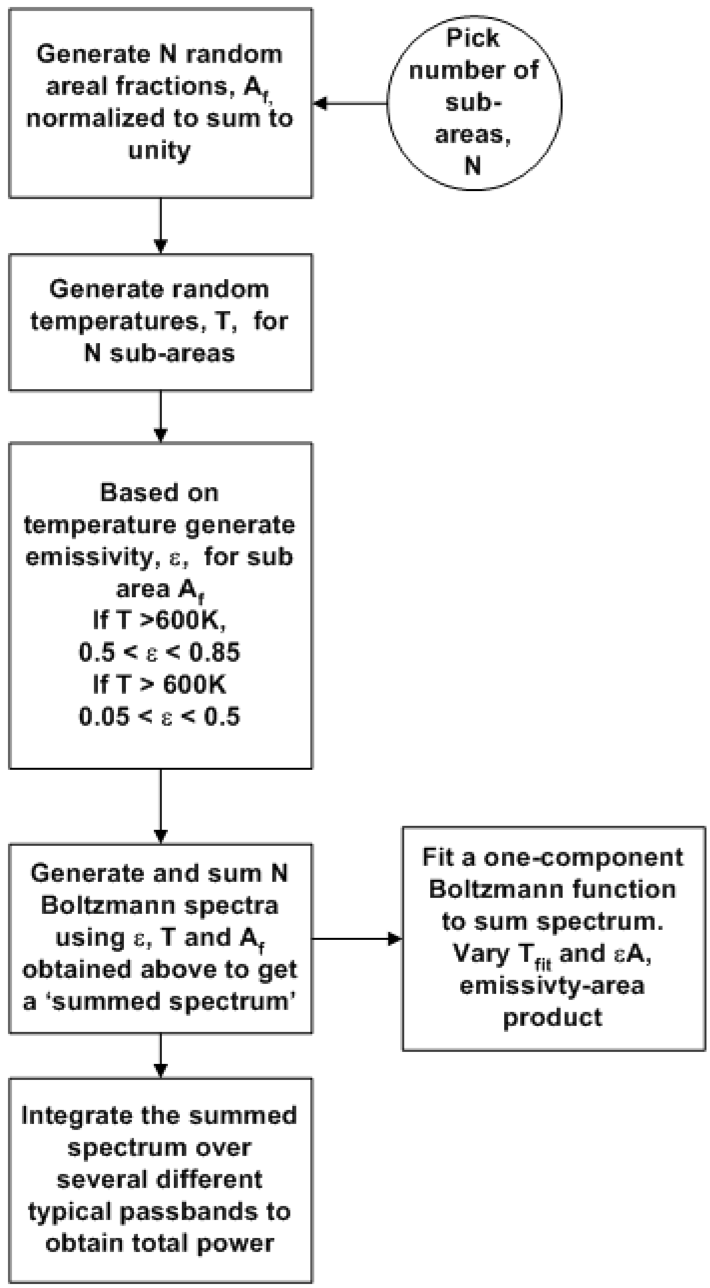
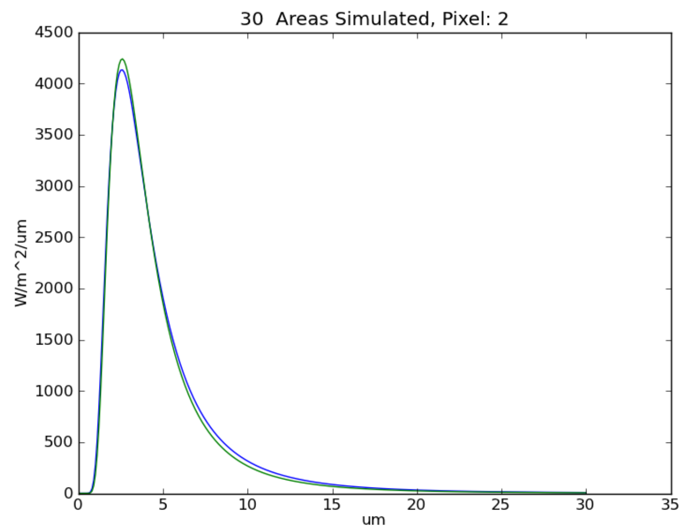
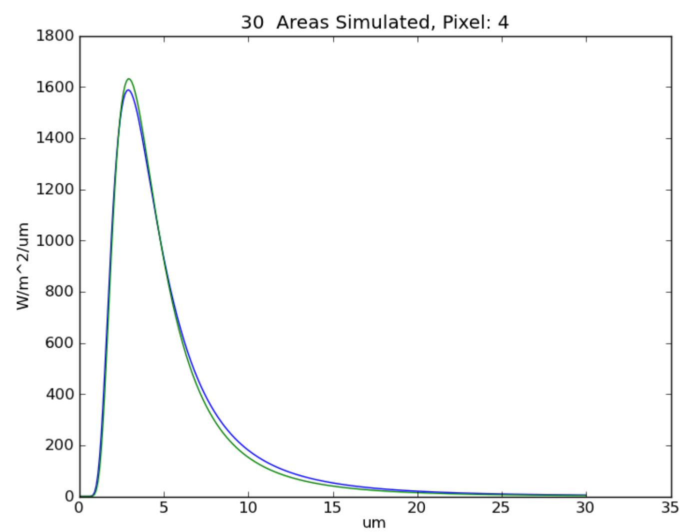


Figure 5 - Graphical examples of the curve fit to simulated data using a single temperature Boltzmann distribution. We show representative examples for pixels with 6 sub-areas within the ground sample area. We varied the temperature and emissivity area product in this two-parameter non-linear fit. Summed spectra (Figure 2) yielding 17.7 kW m^{-2} (A) and 7.6 kW m^{-2} (B).



A



B

Figure 6 - Root mean square error (RMSE) for predicted power for simulations of the mid-wave and long-wave portions of the electromagnetic spectrum and a series of common detectors (). RMSE (W m^{-2}) is from simulations with thirty fractional areas. Atmospheric absorption is not shown in these simulations.

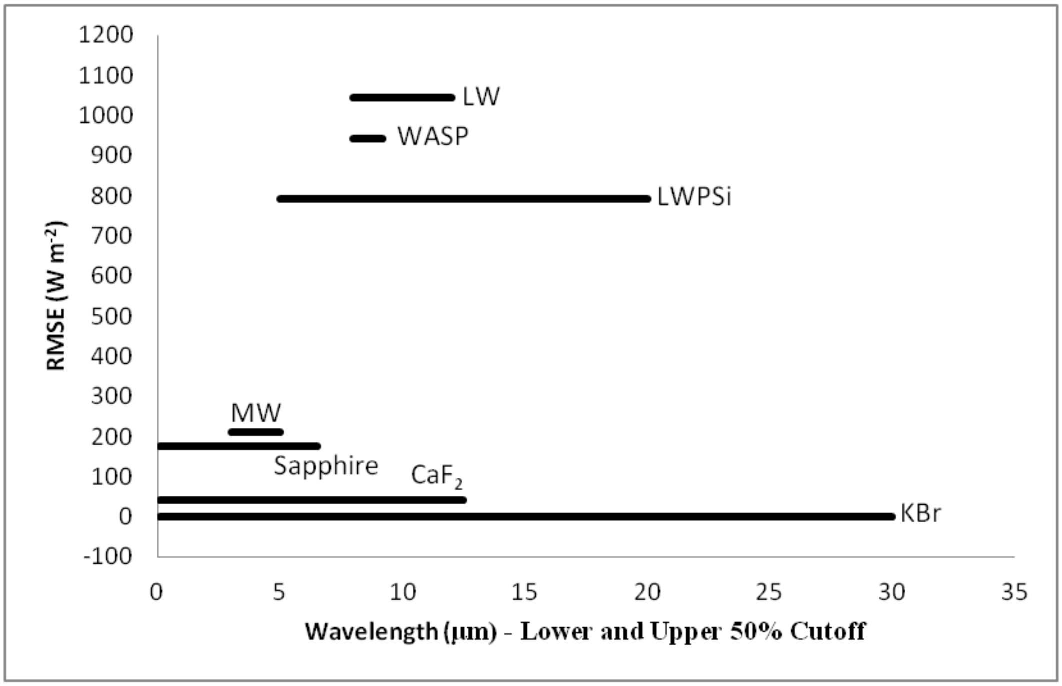
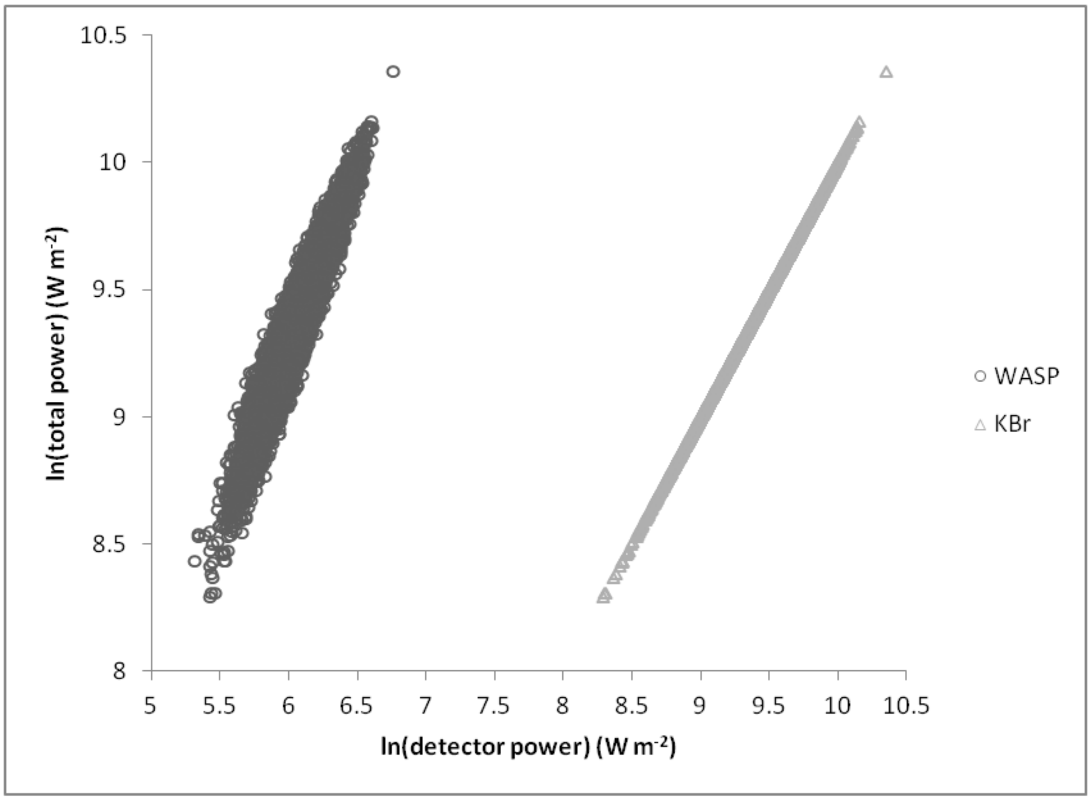


Figure 7 - Example log-linear relationships between total ground-leaving power and power detected by two sensors, one with a restricted bandpass in the long-wave region (WASP) and a detector with a wide bandpass (KBr). See Table 1 and Figure 6 .



Appendix 6

Prichard, Susan, Karau, Eva, Ottmar, Roger, Wright, Clint. A comparison of the Consume and FOFEM fuel consumption models using field data collected in the southeastern United States. Draft manuscript to be submitted as a PNW Research Note in partial fulfillment of JFSP Project Number 08-1-6-01.

Attached to JFSP website: JFSP_08-1-6-01_prichard_draft_manuscript_app6.pdf

A comparison of the Consume and FOFEM fuel consumption models using field data collected in the southeastern United States

Susan Prichard[1], Roger Ottmar[1], Eva Karau[2], and Clint Wright[1]

[1]Pacific Wildland Fire Sciences Lab
400 N 34th St, Suite 201
Seattle, WA 98195
phone: 509-341-4493
email: sprich@uw.edu

[2]Fire Modeling Institute
5775 US Hwy 10 West
Missoula, MT 59808
phone: 406-829-6950
email: ekarau@fs.fed.us

Introduction

Fuel consumption is the amount of biomass consumed during a fire and is one of the critical components for estimating the amount and source strength of emissions, the effectiveness of prescribed for reducing fuels, the rate of heat generated, and numerous fire effects such as soil heating and potential tree mortality. Fuel consumption is especially critical in the eastern region of the United States where prescribed burning is a key fuels reduction and restoration technique (Wade and Lunsford 1989, Marshall et al. 2008) and where increasing expansion and development of the wildland-urban interface requires accurate smoke production estimates from prescribed burns for EPA compliance and to protect public health, particularly in areas with high population density (Theobald and Romme 2007, Zhang et al. 2008).

Although fuel consumption can be measured in the field, the cost often is prohibitive. To reduce this cost and provide a reliable means for estimating fuel consumption, Consume and the First Order Fire effects (FOFEM) were developed by Forest Service Research to provide fuel consumption prediction. However, these models have not been adequately validated. Consume (Prichard et al. 2007, JFSP 2009) is a software application that estimates fuel consumption for wildland fires. Consume contains empirically derived fuel consumption equations specific to fuel category (e.g., shrubs, herbaceous vegetation, litter, duff, and woody fuels by time lag class) that represent the western, southeastern, and boreal forest regions of the United States. It also contains physically based equation with empirically derived constants to predict fuel consumption in recent logging slash. The First Order Fire Effects Model (FOFEM; Reinhardt et al. 1997, Reinhardt 2003) estimates fuel consumption for different regions of the country by fuelbed category using the BURNUP model (Albini, 1994, Albini and Reinhardt 1995, Albini et al. 1995, Albini and Reinhardt, 1997). Burn-up is a mechanistic woody fuel consumption model (Lutes, in review).

Because little research on wildland fuel consumption has been conducted in the eastern regions of the United States, there are few reliable fuel consumption models available and no reliable validation dataset exists to assess the sensitivity, biases, and uncertainties of fuel consumption algorithms currently housed within Consume and FOFEM. The objective of this study was to collect a fuel consumption dataset, including pre- and post-burn fuel characteristics and day-of-burn environmental variables, to (1) help determine each models uncertainties, biases, or application limits in the eastern U.S. and (2) contribute predictive models of fuel consumption in eastern forests. A total of 29 burn units are part of this study and were burned between December and April, 2009 and 2010.

Methods

1. Study areas

Burn units were selected to measure fuel consumption in southern pine forest and sand pine scrub types in the southeastern U.S and mixed hardwoods and pitch pine in the north eastern and north central U.S. (Figure 1, Table 1). A total of 15 southern pine units were burned in Florida and South Carolina and are dominated by longleaf and loblolly pine with saw palmetto and gallberry understories and are generally burned on a three-year rotation. The remaining southern pine units are pond pine/sand live oak sites in Pumpkin Hill State Reserve, Florida that had not been prescribed burned in over 20 years. A total of 11 mixed hardwood units were burned in

Kentucky, Ohio, and Virginia, and units range from open stands with a developed understory to closed stands with little to no understory.

2. Field Measurements

Prior to each burn, preburn fuel loads and other characteristics were collected using a combination of subplots and line intercept transects. For the 18 southern pine sites, surface fuels, including litter, duff and fine woody fuels, were collected in small subplots (0.25 m^2) along systematic grids. All standing vegetation rooted within the boundaries of each subplot was cut at ground level, separated by species and status (live and dead), oven dried, and weighed. Where present, large woody fuels were estimated using a planar intersect inventory (Brown 1974). For the 11 mixed hardwood sites, fine woody fuels were estimated using a planar intersect inventory, and litter and duff consumption was measured using 16 duff pins positioned at the top of the litter layer around each of 20 inventory plots (Beaufait et al. 1977). Shrub and herbaceous vegetation were sampled in subplots located along sampling transects.

Day-of-burn fuel moistures and weather variables were collected immediately prior to each prescribed burn. As various burn units came into prescription, a field crew was dispatched to install weather monitoring equipment adjacent to the burn unit and to collect live and dead fuel moisture samples on the day of the burn. On the day of each burn, field personnel assisted with burn operations as needed and made observations of within-unit weather. Following prescribed burns, the crew remained to perform post-burn fuel sampling using pre-burn sampling protocols.

3. Model Parameterization

For the 29 study sites, we parameterized FOFEM and Consume with data collected prior to burning. Inputs in common to both models include: herbaceous, shrub, 1-hour, 10-hour, 100-hour, and 1000-hour fuel loads and 10-hour, 1000-hour and duff fuel moisture content. Additional FOFEM 5.9 inputs include forest cover type (SAF 70, 3-yr rough), season of burn (winter/spring), duff depth, duff load, litter load, and percent of rotten logs. Default FOFEM settings include region (Southeast), fire type (moderate), and consumption (natural-fuel). In four units (GWJ_JR, GWJ_CM, MBGH, A34), the measured duff load or moisture content was out of the range of FOFEM hard limits, and we entered the nearest acceptable value. Additional Consume 4.1 inputs include percent live (i.e., the percentage of living biomass) for shrub and herbaceous fuel components, an estimate of "percent black" for the shrub stratum (i.e., the percentage of the shrub stratum blackened by the prescribed burn), litter depth, percent cover of litter, litter arrangement (normal), duff depth, duff derivation (upper), and duff percent cover (Table 4).

Several burn units lack measurements of pre-fire fuel characteristics and fuel moistures, indicated by blank cells in Table 4. Because burns were conducted in the dormant season, all units that had herbaceous (i.e., nonwoody vegetation) fuel loads were assigned a percent live of 0%. For units with no recorded duff percent cover, we used litter percent cover. For units in which fuel moisture measurements were not taken, a calculated average was used. Average 10hr FM was calculated from all sites with reported 10-hr FM excluding E807D and A34 which had extremely high values. Average 1000hr FM was calculated from all sites with reported 1000hr FM excluding E807D, which had an extremely high value. Finally, a default value of 50% percent black was used for DB_WSLF.

Data Analysis

FOFEM and Consume were used to predict consumption of the following fuel components: herbaceous, shrub, 10-hour, 100-hour, 1000-hour sound, 1000-hour rotten, litter, and duff. For each fuel category we plotted predicted consumption versus measured consumption. To assess model performance, we conducted a model equivalence test, which tests against the hypothesis that models are dissimilar (Robinson and Froese 2004, Robinson et al. 2005).

Results

Pre-fire fuel and fuel consumption

The pine units in this study were frequently burned with generally low pre-fire fuel loading measured for the shrubs, herbaceous, litter, duff, and woody fuelbed categories and ranged from 2.1 tons/acre to 9.3 tons/acre. In all cases, the duff was nonexistent and no measurements were collected. The mixed hardwood units had a longer period between fires and the loadings were substantially higher than in the pine units, and preburn fuel loading ranged from 10.3 tons/acre to 34.6 tons per acre (Figure 2). Although more fuel consumption was measured on the mixed hardwood sites, it was limited. In the pine sites, total fuel consumption ranged from 0.7 tons/acre to 5.28 tons/acre (Figure 3).

Fuel Consumption Comparison—Consume and FOFEM

Scatter plots (Figure 4) display predicted consumption by FOFEM and Consume compared to measured fuel consumption. A perfect fit between predicted versus measured consumption would be reflected in a linear regression model with an intercept of zero and slope of 1. This study encompassed markedly different vegetation types with 18 southern pine and 11 mixed hardwood units. Due to the relatively small sample size, we elected to pool the datasets. Examination of model residuals by plot suggest that with the exception of fine woody fuels, there are no discernible differences in model fit between the 18 pine sites and 11 mixed hardwood sites (Figure 5). The following is a summary of general trends and model behavior by each stratum.

Shrub consumption -- Consume and FOFEM predictions of shrub consumption are highly correlated to measured shrub consumption (Table 4). Consume predictions are somewhat closer to measured consumption values with an R^2 of 0.94 compared to an R^2 of 0.81 for the FOFEM predictions.

Herbaceous consumption -- FOFEM and Consume accurately predict herbaceous fuel consumption for 18 of the 29 units that contained an herbaceous vegetation layer. Both models predict values that are strongly correlated ($R^{2\,=}$ 0.97) with measured herbaceous fuel consumption and with slopes near 1 and intercepts near zero. Only 18 of the 29 units had an herbaceous fuel layer, including all southern pine units and only one mixed hardwood unit. The mixed hardwood unit (DBWSLF) was excluded as an outlier because of its extremely low measured consumption versus modeled consumption. The Consume model predictions are equivalent with measured consumption at $\alpha = 0.1$.

1-hour fuel consumption – Both models tend to over-predict 1-hr fuel consumption and are particularly poor for the mixed hardwood sites (Figure 5). Measured 1-hr fuel consumption ranges from 25 to 100%. Consume assumes that all 1-hr fuels will consume, regardless of input fuel moisture whereas FOFEM predictions vary by fuel moisture. FOFEM also predicts that the majority of units would have 100% 1-hr fuel consumption.

10-hour fuel consumption -- Both models over-predict 10-hr fuel consumption and are better at predicting the fuel consumption for the southern pine sites than the mixed hardwood sites (Figure 5). FOFEM has a slightly better fit with measured consumption than Consume (R^2 = 0.75 versus 0.65).

100-hour fuel consumption – Consume predictions of 100-hour fuel consumption have a better fit with measured consumption values (R^2 = 0.81) than FOFEM predictions (R^2 = 0.66). As with other fine wood categories, predictions are better for southern pine units than mixed hardwood units (Figure 5).

Large fuel consumption (> 3 inch diameter) – Consume predictions of large wood consumption are highly correlated with measured consumption (R^2 = 0.99) with a nearly 1:1 model fit across all units and were found to be equivalent with measured consumption at α = 0.1. FOFEM predictions consistently under-predict measured fuel consumption (R^2 = 0.23).

Litter consumption – Neither model performs well in predicting litter consumption. FOFEM predicts 100% litter consumption for all sites whereas measured litter consumption ranges from 0 to 82%. Consume predictions are based on input litter depth (not loading), and are extremely low for input litter depths less than one inch. Consume also predicts greater consumption than preburn loading for two units (E807B and E807D), partly due to a large discrepancy in calculated versus measured preburn loading.

Duff consumption—Consume and FOFEM predicted 0% consumption for the majority of mixed hardwood and pitch pine units. There was no duff present in the pine units due to their frequent burn rotation. Measured duff consumption in the mixed hardwood units ranges from 4 to 71% consumption. In contrast, Consume and FOFEM predict 0% consumption for all of these sites.

Discussion

Overall, Consume and FOFEM perform well in predicting shrub and herbaceous consumption. Model predictions are worse for the 1-hr, 10-hr, and 100-hour woody fuel consumption, in mixed hardwood sites while model residuals (3) indicate a better fit between predicted and measured 10-hr and 100-hr consumption for southern pine units than mixed hardwood units. Consume predictions of large woody fuels (> 3 inch diameter) have high correspondence to measured fuel consumption. The clear difference in model residuals between southern pine and mixed hardwood units suggest that separate equations may be necessary to predict fine woody fuel consumption in these different eastern forest types.

The near-perfect fit between predicted and measured large woody fuel consumption is somewhat surprising. Consume 4.1 actually uses a combination of regression models by sound and rotten wood and timelag class (1000-hr, 10,000-hr, >10,000hr). However, the majority of the fuels are in the 1000-hr category and these equations were developed from regression modeling in southern pine fuel consumption trials with similar fuel characteristics and under similar burning conditions.

Both models do a poor job of predicting litter consumption. Inconsistent measures of pre-burn litter loads and duff FM likely contributed low correspondence between modeled and measured litter consumption. In addition, Consume calculates pre-burn loading from input litter depth and percent cover, and calculated preburn loads differ substantially from measured preburn loads for several units. Duff FM is a predictor variable of litter reduction in the Consume model and was only recorded for some units. In addition, pre- and postburn litter loads were sampled differently between the southern pine and mixed hardwood units. Use of clip plots in the southern pine units likely contributed error in fuel consumption estimates because sampling locations varied between pre- and post-measurements whereas use of litter and duff reduction pins was likely more accurate in the mixed hardwood sites.

Both models predicted 0% duff consumption in mixed hardwood sites whereas measured duff consumption ranged from 72-99%. Thresholds for duff consumption at high duff fuel moistures are likely greater than allowed for in both models.

Results of this model validation study suggest that both models can be improved in their predictive equations of fine woody fuel, litter, and duff consumption for the eastern United States. The apparent similarity in fuel characteristics and model predictions between the two major vegetation types sampled in this study (southern pine and mixed hardwood forests) suggest that with the exception of fine woody fuels, it may be possible to combine existing consumption datasets to develop more robust predictive equations. More work is clearly needed to develop reliable models of litter and duff consumption for eastern forest types.

Acknowledgements

We thank the Joint Fire Science Program for the financial assistance in providing the opportunity to complete this comparison and thank our cooperators including John Ashcraft, Mammoth Caves National Park, Bob Broyles, Ohio Division of Forestry, Mike Bowden, Ohio Division of Forestry, Jeffrey Lewis, Daniel Boone National Forest, Steve Smestad and Steve Croy, George Washington and Jefferson National Forest, Eugene Watkins, Apalachicola National Forest, Greg Titus, St. Marks National Wildlife Refuge, and Kevin Heirs and Brett Williams, Jackson Guard, Eglin Air Force. We also thank Jon Dvorak, Shawn Smith, Travis Freed, Jon McDuffey, Joe Restaino, Cameron Balog, Aarin Sengsirirak, and Jim Cronan for their hard work in collecting the data. Finally, we greatly appreciate Maureen Kennedy who provided guidance on the statistical analysis.

References

Albini, F.A. 1994. Program Burnup: A simulation model of the burning of large woody natural fuels. Unpublished final report for Research Grant INT-92754-GR. On file at the USDA, Forest Service, RMRS, Missoula Fire Science Laboratory, Missoula, MT.

Albini, F.A., Reinhardt, E.D., 1995. Modeling ignition and burning rate of large woody natural fuels. International Journal of Wildland Fire. 5(2):81-91.

Albini, F.A., Brown, J.K., Reinhardt, E.D., Ottmar, R. D. 1995. Calibration of a large fuel burnout model. International Journal of Wildland Fire. 5(3):173-192.

Albini, F.A., Reinhardt, E.D., 1997. Improved calibration of a large fuel burnout model. International Journal of Wildland Fire. 7(1):21-28.

Beaufait, William R., Hardy, Charles, E., Fisher, William C. 1977. Broadcast burning in larch-fir clearcuts: The Miller Creek-Newman Ridge study. Res. Pap. INT-175, US Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT. 73 p.

Brown, J.K. 1974. Handbook for inventorying downed woody material. GTR-INT-016. US Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Joint Fire Science Program. 2009. Consume 3.0--a software tool for computing fuel consumption**.** Fire Science Brief. 66, June 2009. 6 p

Lutes, Duncan C. In review. Predicted Fuel Consumption in the Burnup model: Sensitivity to four user inputs. Rocky Mountain Station Research Note.

Marshall, D.J., Wimberly, M., Bettinger, P. Stanturf, J. 2008. Synthesis of knowledge of hazardous fuels management in loblolly pine forests. GTR-SRS-110, U.S. Forest Service, Southern Research Station, Asheville, NC.

Prichard, S.J., Ottmar, R.D., Anderson, G.K. 2007. Consume user's guide and scientific documentation (online) http://www.fs.fed.us/pnw/fera/research/smoke/consume/consume30_users_guide.pdf

Reinhardt, E. 2003. Using FOFEM 5.0 to estimate tree mortality, fuel consumption, smoke production and soil heating from wildland fire. Presentation at the 2nd International Wildland Fire Ecology and Fire Management Congress, 16-20 November 2003, Orlando, FL. 6 p.

Reinhardt, E.D.; Keane, R.E., Brown, J.K. 1997. First order fire effects model: FOFEM. USDA Forest Service General Technical Report INT-GTR-344. 65 p.

Robinson, A.P., Froese, R.E. 2004. Model validation using equivalence tests. Ecol. Model. 176:349-358.

Robinson, A.P., Duursma, R.A., Marshall, J.D. 2005. A regression-based equivalence test for model validation: shifting the burden of proof. Tree Phys. 25, 903-913.

Theobald, D.M., Romme, W.H. 2007. Expansion of the U.S. wildland-urban interface. Landscape Urban Plan. 83, 340-354.

Wade, D.D., Lunsford, J.D. 1989. A guide for prescribed fire in southern forests.US Forest Service, Southern Region Technical Publication R8-TP-11, Atlanta, GA.

Zhang, Y. He, H.S., Yang, J. 2008. The wildland–urban interface dynamics in the southeastern U.S. from 1990 to 2000. Landscape Urban Plan. 85, 155-162.

Table 1: Eastern fuel consumption study locations and site descriptions

#	Unit	Location	Latitude	Longitude	Burn date	Fuelbed type	Ignition type	Ignition length (min)	Site Description
1	AP018	Appalachicola NF, FL	30.2089	-84.8599	2/11/2010	Pine	Helicopter	3.75	Long leaf pine plantation with understory of palmetto, gallberry, other shrub and grass.
2	AP034	Appalachicola NF, FL	30.2026	-84.8345	2/18/2010	Pine	Hand	4	Same as AP018
5	AP050	Appalachicola NF, FL	30.1375	-84.7746	2/7/2009	Pine	Helicopter	360	Same as AP018
3	AP213	Appalachicola NF, FL	30.3423	-84.5412	2/11/2010	Pine	Hand	2.75	Same as AP018
6	AP312	Appalachicola NF, FL	30.1957	-84.6313	1/24/2009	Pine	Helicopter	120	Same as AP018
4	AP319	Appalachicola NF, FL	30.2184	-84.4205	1/14/2010	Pine	Hand	3.25	Same as AP018
7	AP320	Appalachicola NF, FL	30.2432	-84.4685	2/17/2009	Pine	Helicopter	240	Same as AP018
8	AP328	Appalachicola NF, FL	30.1309	-84.6327	1/31/2009	Pine	Helicopter	240	Same as AP018
9	E100BE	Eglin AFB, SC	30.6566	-86.7145	1/12/2010	Pine	Hand	4	Same as AP018
10	E501B	Eglin AFB, SC	30.4569	-86.7618	12/23/2009	Pine	Hand	5.75	Same as AP018
11	E505	Eglin AFB, SC	30.4614	-86.6688	1/23/2010	Pine	Hand	1.75	Same as AP018
12	E807B	Eglin AFB, SC	30.4847	-86.2767	1/4/2010	Pine	Hand	2.5	Same as AP018
13	E807D	Eglin AFB, SC	30.5034	-86.2570	2/21/2010	Pine	Hand	5	Same as AP018
14	PH1V	Pumpkin Hill State Park Reserve, FL	30.4729	-81.4926	2/10/2009	Pine	Hand	240	Pond pine forest with understory of sand live oak, palmetto, and wiregrass
15	PH1V2	Pumpkin Hill State Park Reserve, FL	30.4729	-81.4926	2/27/2009	Pine	Hand	270	Same as PH1V
16	PH2K	Pumpkin Hill State Park Reserve, FL	30.4719	-81.4897	2/27/2009	Pine	Hand	135	Pond pine savannah with patchy understory of palmetto and oak interspersed with bare mineral soil
17	S121	Saint Marks Wildlife Refuge, FL	30.1433	-84.1317	3/19/2009	Pine	Hand	60	Long leaf pine forest with understory dominated by palmetto component with some oak species.
18	S330	Saint Marks Wildlife Reserve, FL	30.0783	-84.3743	2/17/2010	Pine	Hand	4	Long leaf pine forest with understory of palmetto, gallbery, and wiregrass
19	DBBCLF	Daniel Boone NF, KY	38.0526	-83.5543	4/18/2009	Hardwood	Helicopter	270	Mixed hardwood forest with open greenbriar understory
20	DBCCLF	Daniel Boone NF, KY	38.0435	-83.5500	4/18/2009	Hardwood	Helicopter	390	Mixed hardwood forest with understory of red maple and greenbrier.
21	DBWPLF	Daniel Boone NF, KY	38.0608	-83.5802	4/17/2009	Hardwood	Helicopter	210	Same as DBBCLF
22	DBWSLF	Daniel Boone NF, KY	38.0882	-83.5783	3/23/2009	Hardwood	Hand	300	Mixed forest, with hardwood species, shortleaf pine, and pitch pine. Understory dominated by red maple and greenbrier.
23	GWJCM	George Washington & Jefferson NF, VI/KY	37.7554	-79.2114	4/9/2009	Hardwood	Hand.	300	Mixed hardwood forest with red maple understory.
24	GWJJR	George Washington & Jefferson NF, VI/KY	38.1350	-79.7911	4/17/2009	Hardwood	Helicopter	285	Same as GWJCM
25	MBHG	Mammoth Caves NP, KY	37.1811	-86.0999	3/31/2009	Hardwood	Hand	360	Mixed hardwood forest with little to no understory.
26	MFM2	Mammoth Caves NP, KY	37.2093	-86.0816	4/1/2009	Hardwood	Hand	360	Mixed hardwood forest with a midstory of maple, dogwood,

									and cedar. Little to no understory.
27	MJC	Mammoth Caves NP, KY	37.1763	-86.1134	4/2/2009	Hardwood	Hand	480	Same as MFM2
28	THA	Tar Hollow State Park, OH	39.3660	-82.7770	4/13/2009	Hardwood	Helicopter	270	Mixed hardwood forest with a midstory of maple and American beech. Little to no understory.
29	THB PLOH	Tar Hollow State Park, OH	39.3490	-82.7580	4/13/2009	Hardwood	Helicopter	90	Mixed hardwood forest with heavy greenbriar understory.

Table 2: Consume and FOFEM inputs in addition to preburn fuel loads, which are presented in Table 3. NP = not present. Blank cells indicate where fuel moistures were not collected.

#	Unit	Live shrub (%)	Blackened shrub (%)	Litter depth (in)	Litter cover (%)	Duff cover (%)	Duff depth (in)	10hr FM (%)	1000hr FM (%)	Duff FM (%)	Rotten log (%)
1	AP018	93	100	0.67	64.9	64.91	0.24	61.4		NP	52.94
2	AP034	75	100	0.59	57.3	57.33	0.04	74		NP	100.00
5	AP050	96	99	0.67	59.9	NP	NP	22.6	92.95	NP	14.71
3	AP213	79	94	0.83	94.5	94.45	0.12	54.9		NP	41.73
6	AP312	75	95	1.11	68.6	NP	NP	56	101.01	NP	61.11
4	AP319	85	99	0.87	95.2	95.21	0.47	48.9		NP	16.98
7	AP320	76	100	0.84	58.9	NP	NP	60.3	84.22	NP	55.81
8	AP328	73	99	1.07	53.4	NP	NP	56.4	65.55	NP	71.43
9	E100BE	91	99	0.83	87.7	87.71	0.67	40	123.09	NP	51.79
10	E501B	84	100	0.94	52.8	NP	NP			NP	50.00
11	E505	90	65	0.79	77.8	77.75	0.59	66.5	113.75	NP	67.14
12	E807B	92	51	0.87	88	87.99	2.28			NP	42.34
13	E807D	84	99	1.06	91.9	91.89	1.22	81.2	140.00	NP	100.00
14	PH1V	75	73	0.79	97.4	NP	NP	13.7		NP	0.00
15	PH1V2	75	88	0.72	92.4	NP	NP	9.89		NP	0.00
16	PH2K	77	50	0.49	78.7	NP	NP	9.89		NP	26.32
17	S121	88	53	0.83	95	NP	NP	32		NP	54.17
18	S330	94	96	0.94	91	90.98	0.12	57.5		NP	100.00
19	DBBCLF	100	91.86	1.71	89.3	90.22	0.6	13.7	69.50	75.16	59.87
20	DBCCLF	100	52.85	1.45	93.4	94.39	0.62	42.6	58.20	172.85	30.44
21	DBWPLF	100	80.86	1.82	96	95.64	0.45	23.2	82.45	191.08	46.93
22	DBWSLF	100	50	2.07	98.7	100	0.68	20.3	67.50	77.91	73.27
23	GWJCM	NP	NP	1.7	98.7	99.36	1.2	50.3	73.50	349.51	46.20
24	GWJJR	100	98.43	2.45	99	99.67	0.9	39.6	73.34	272.91	51.25
25	MBHG	NP	NP	1.41	95.3	82.24	0.2	34.7	57.90		94.41
26	MFM2	NP	NP	1.35	97.4	95.42	0.39	25.7	71.90		72.08
27	MJC	NP	NP	1.85	94.9	92.34	0.25	27.3	76.30	67.49	28.27
28	THA	NP	NP	1.34	98	96.98	0.47	9.64	59.10	59.67	84.64
29	THB _PLOH	93	95.61	2.17	96.7	97.45	0.42	13.1	52.10	47.21	52.98

Table 3: Preburn fuel loads (Pre), measured fuel consumption (Meas) and predicted fuel consumption from Consume 4.1 (C) and FOFEM 5.9 (F). All units are in tons/acre. NP = fuel category not present. Blank cells indicate where measures were not taken.

	Shrub				**Herbaceous**				**Litter**				**Duff**			
Unit	**Pre**	**Meas**	**C**	**F**	**Pre**	**Meas**	**C**	**F**	**Pre**	**Meas**	**C**	**F**	**Pre**	**Meas**	**C**	**F**
AP018	1.34	1.17	1.21	0.71	0.39	0.34	0.36	0.39	0.91	0	0.02	0.91	NP	NP	NP	NP
AP034	0.76	0.44	0.68	0.4	0.21	0.21	0.19	0.21	0.71	0	0.01	0.71	NP	NP	NP	NP
AP050	2.29	1.99	2.07	2.29	0.39	0.34	0.36	0.39	0.84	0.08	0.01	0.84	NP	NP	NP	NP
AP213	1.57	1.13	1.37	0.88	0.01	0.01	0.01	0.01	1.66	0.10	0.02	1.66	NP	NP	NP	NP
AP312	3.44	2.58	3.09	3.44	0.12	0.13	0.11	0.12	1.61	0.28	0.53	1.61	NP	NP	NP	NP
AP319	1.89	1.61	1.70	1.3	0.09	0.09	0.08	0.09	1.74	0.44	1.15	1.74	NP	NP	NP	NP
AP320	2.79	2.31	2.54	2.79	0.21	0.21	0.19	0.21	1.04	0	0.01	1.04	NP	NP	NP	NP
AP328	1.46	0.92	1.42	1.58	0.41	0.41	0.38	0.41	1.19	0	0.01	1.19	NP	NP	NP	NP
E100BE	2.07	1.14	1.87	1.52	0.08	0.08	0.07	0.08	1.53	0	1.32	1.53	NP	NP	NP	NP
E501B	1.40	1.17	1.26	0.81	0.12	0.11	0.11	0.12	1.05	0.56	0.01	1.05	NP	NP	NP	NP
E505	1.04	0.15	0.65	0.7	0.06	0.03	0.06	0.06	1.29	0.91	0.99	1.29	NP	NP	NP	NP
E807B	2.00	0.86	0.97	2	0.15	0.08	0.14	0.15	1.61	1.22	2.30	1.61	NP	NP	NP	NP
E807D	1.65	1.37	1.48	1.65	0.02	0.02	0.02	0.02	2.05	1.44	2.71	2.05	NP	NP	NP	NP
PH1V	4.77	4.11	3.71	4.77	0.03	0.02	0.03	0.03	1.61	0.55	0.02	1.61	NP	NP	NP	NP
PH1V2	4.77	4.4	4.18	4.77	0.03	0.02	0.03	0.03	1.39	0.36	0.02	1.39	NP	NP	NP	NP
PH2K	4.62	2.51	2.48	4.08	0.02	0.02	0.02	0.02	0.81	0.30	0.02	0.81	NP	NP	NP	NP
S121	3.76	1.15	2.08	3.76	0.10	0.10	0.09	0.1	1.66	1.36	0.02	1.66	NP	NP	NP	NP
S330	1.27	0.69	1.12	0.68	0.24	0.24	0.22	0.24	1.80	0	0.02	1.80	NP	NP	NP	NP
DBBCLF	0.06	0	0.05	0.06	NP	NP	NP	NP	2.01	1.66	1.30	2.01	1.65	0.44	0	0
DBCCLF	0.01	0	0	0	NP	NP	NP	NP	1.52	0.67	0.01	1.52	1.65	0.05	0	0
DBWPLF	0.04	0	0.03	0	NP	NP	NP	NP	1.96	1.51	0.01	1.96	2.44	0.4	0	0
DBWSLF	9.87	0.02	6.49	7.1	0.19	0	0.18	0.19	1.68	1.43	1.81	1.68	2.38	0.51	0	0
GWJCM	NP	NP	NP	NP	NP	NP	NP	NP	2.07	1.23	0.01	2.07	4.36	0.14	0	0
GWJJR	0.02	0.02	0.02	0.02	NP	NP	NP	NP	2.68	2.21	0.60	2.68	4.14	0.23	0	0
MBHG	NP	NP	NP	NP	NP	NP	NP	NP	1.13	0.88	0.81	1.13	0.42	0.07	0	0
MFM2	NP	NP	NP	NP	NP	NP	NP	NP	1.16	0.94	0.95	1.16	3.47	0.73	0	0
MJC	NP	NP	NP	NP	NP	NP	NP	NP	1.89	1.48	1.26	1.89	1.07	0.52	0	0
THA	NP	NP	NP	NP	NP	NP	NP	NP	1.71	1.12	1.11	1.71	2.52	0.34	0	0
THB _PLOH	0.32	0.25	0.28	0.32	NP	NP	NP	NP	1.76	1.38	1.90	1.76	1.61	0.18	0	0

Table 3: cont.

Unit	1hr				10hr				100hr				>=1000hr			
	Pre	Meas	C	F	Pre	Meas	C	F	Pre	Meas	C	F	Pre	Meas	C	F
AP018	0.03	0.02	0.03	0.01	0.24	0.03	0.21	0	0.17	0	0.07	0	0.34	0	0.02	0
AP034	0.02	0	0.02	0	0.17	0	0.15	0	0.14	0.01	0.06	0	0.11	0	0.01	0
AP050	0.22	0.18	0.22	0.22	0.63	0.27	0.54	0.63	0.35	0.06	0.14	0.26	0.34	0	0.02	0
AP213	0.01	0.01	0.01	0	0.14	0	0.12	0	0.32	0.01	0.13	0	1.27	0	0.10	0
AP312	0.16	0.04	0.16	0.09	0.67	0.4	0.58	0	0.97	0.13	0.39	0	2.16	0	0.08	0
AP319	0.10	0.08	0.10	0.10	0.18	0	0.16	0	0.26	0.03	0.10	0	0.53	0	0.03	0
AP320	0.11	0.1	0.11	0.04	0.18	0	0.16	0	0.49	0.03	0.20	0	0.86	0.06	0.05	0
AP328	0.08	0.05	0.08	0.03	0.33	0.13	0.29	0	0.24	0.05	0.10	0	0.98	0	0.08	0
E100BE	0.10	0.08	0.10	0.10	0.43	0	0.37	0.43	0.64	0.04	0.26	0.22	4.46	0	0.15	0
E501B	0.06	0.04	0.06	0.05	0.23	0	0.20	0.04	0.34	0.02	0.14	0	2.46	0	0.28	0
E505	0.06	0.01	0.06	0.06	0.32	0	0.28	0	0.48	0	0.19	0	2.13	0	0.07	0
E807B	0.13	0.05	0.13	0.13	0.48	0	0.42	0.48	0.93	0.03	0.37	0.62	1.11	0	0.07	0.06
E807D	0.09	0.04	0.09	0.09	0.25	0	0.22	0.1	0.46	0.02	0.19	0	0.1	0	0	0
PH1V	0.20	0.2	0.20	0.20	0.3	0.24	0.26	0.3	0.22	0	0.09	0.22	0.09	0	0.01	0
PH1V2	0.20	0.2	0.20	0.20	0.35	0.3	0.30	0.35	0.22	0	0.09	0.22	0.09	0	0.01	0.09
PH2K	0.16	0.08	0.16	0.16	0.13	0.02	0.11	0.13	0.05	0.06	0.02	0.05	0.19	0	0.01	0
S121	0.10	0.04	0.10	0.10	0.47	0.13	0.41	0.47	0.33	0.01	0.13	0	0.72	0	0.04	0
S330	0.03	0	0.03	0.01	0.33	0	0.29	0	0.25	0.07	0.10	0	0.27	0.15	0.04	0
DBBCLF	0.32	0.2	0.32	0.32	1.59	0.81	1.38	1.59	3	0.77	1.21	2.17	8.92	1.34	1.23	0.11
DBCCLF	0.26	0.05	0.26	0.26	1.21	0.15	1.05	0.61	2.08	0.36	0.84	0	6.8	0.93	0.93	0
DBWPLF	0.29	0.15	0.29	0.29	1.57	0.56	1.36	1.57	2.53	0.68	1.02	1.11	14.68	1.22	1.19	0.03
DBWSLF	0.36	0.21	0.36	0.36	1.59	0.84	1.38	1.59	2.69	0.7	1.08	1.76	15.6	2.97	2.79	0.18
GWJCM	0.25	0.06	0.25	0.17	1.43	0.17	1.24	0	2.03	0.13	0.82	0	4.87	0.45	0.45	0
GWJJR	0.20	0.07	0.20	0.20	1.2	0.38	1.04	0.66	1.2	0.23	0.48	0	2.81	0.13	0.13	0
MBHG	0.32	0.13	0.32	0.32	1.27	0.44	1.10	0.81	0.64	0.1	0.26	0	7.51	2.27	2.27	0
MFM2	0.37	0.41	0.37	0.37	1.47	1.28	1.27	1.43	1.83	0.67	0.74	0.53	9.85	1.66	1.65	0.01
MJC	0.22	0.13	0.22	0.22	1.17	0.46	1.01	0.91	1.72	0.35	0.69	0.01	5.66	0.54	0.54	0
THA	0.26	0.21	0.26	0.26	1.24	0.78	1.07	1.24	1.63	0.58	0.66	0.96	5.6	1.34	1.32	0.02
THB _PLOH	0.30	0.18	0.30	0.30	1.33	0.64	1.15	1.33	1.53	0.5	0.62	0.93	3.36	0.87	0.67	0.2

Table 4. Fit statistics and model parameters by fuel stratum.

	R2	**RMSE**	**n**	**Intercept**	**Slope**	**Prob(F)**	**Notes on outliers**
Shrub							DBWSLF (low measured
Consume	0.9376	0.3054	23	-0.2186	1.0215	< 001	consumption)
FOFEM	0.8062	0.5382		0.1112	0.7115	< 001	
Herbaceous							DBWSLF (low measured
Consume	0.9678	0.0227	18	-028	1.0164	< 001	consumption)
FOFEM	0.9714	0.0214		-028	0.9364	< 001	
1hr wood							Capped PH1V consumption
Consume	0.6415	0.0521	29	-095	0.6500	< 001	at preburn fuel load
FOFEM	0.6618	0.0506		035	0.6175	< 001	
10hr wood							
Consume	0.6505	0.1975	29	-0.0868	0.5821	< 001	none
FOFEM	0.7477	0.1678		0.0179	0.5121	< 001	
100hr wood							
Consume	0.8114	0.1117	29	-0.0605	0.6609	< 001	none
FOFEM	0.6591	0.1502		0.0775	0.3743	< 001	
3+ wood							
Consume	0.9890	0.0822	29	-0.0386	1.0568	< 001	none
FOFEM	0.2305	0.6891		0.3010	7.4316	< 049	
Litter							
Consume	0.2772	0.3472	28	0.2576	0.2803	050	E100BE (no post-burn litter
FOFEM	0.1111	0.3850		-0.1055	0.3603	0.0464	consumption measurement)

R^2 = coefficient of determination, RMSE = root mean square error, n = sample size, Prob(F) = significance of the linear regression model.

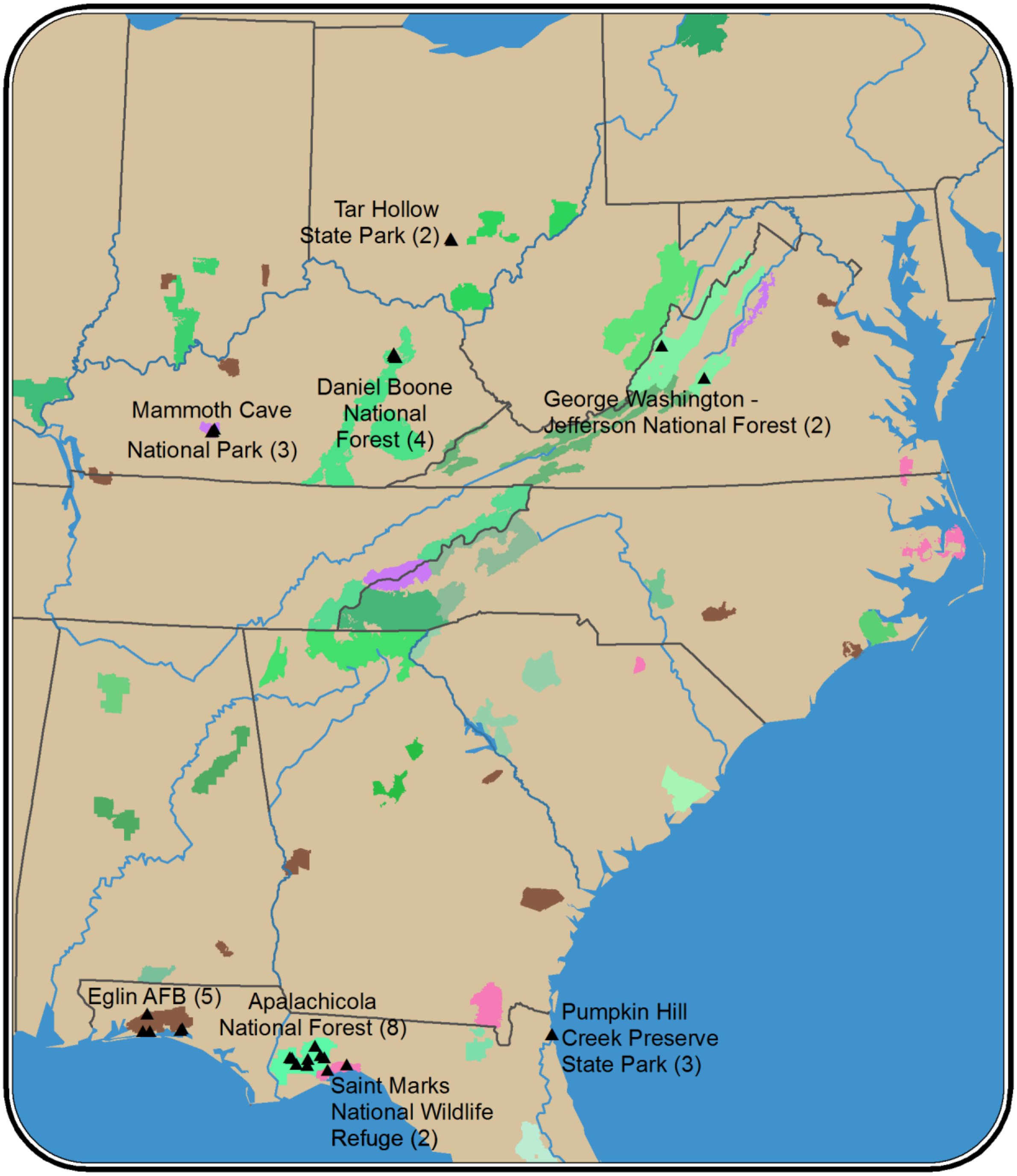


Figure 8. Location of 29 burn units.

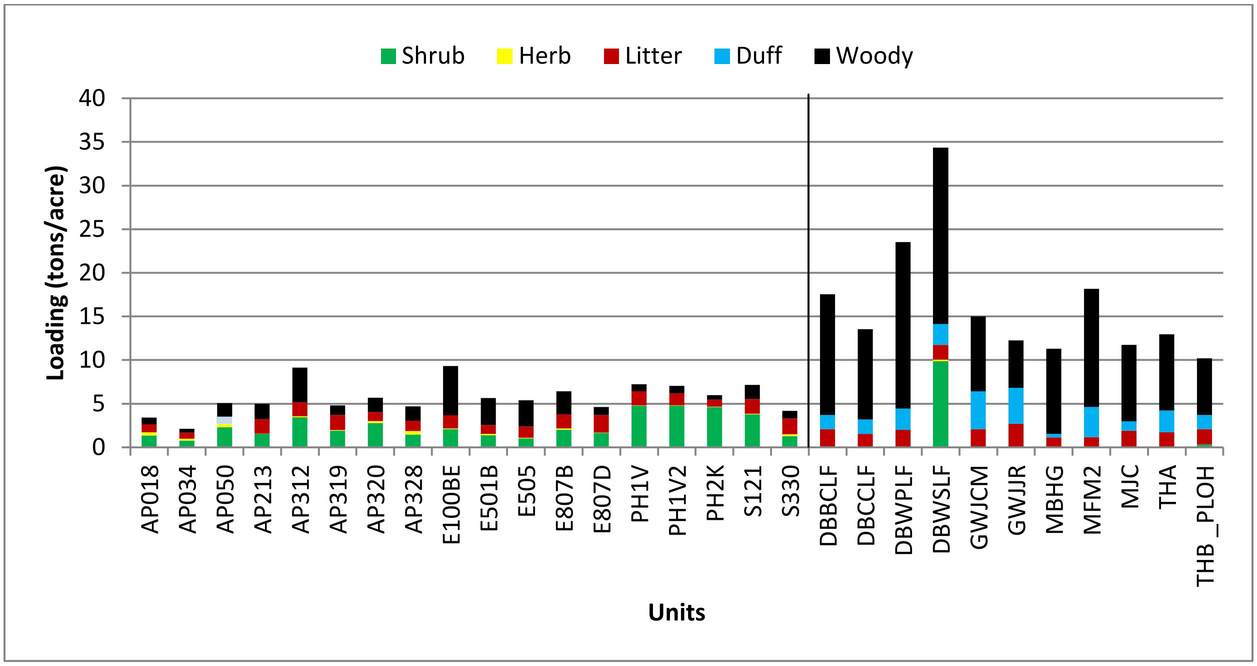


Figure 9. Fuel loading by fuelbed category. Pine study sites are to the left of the line.

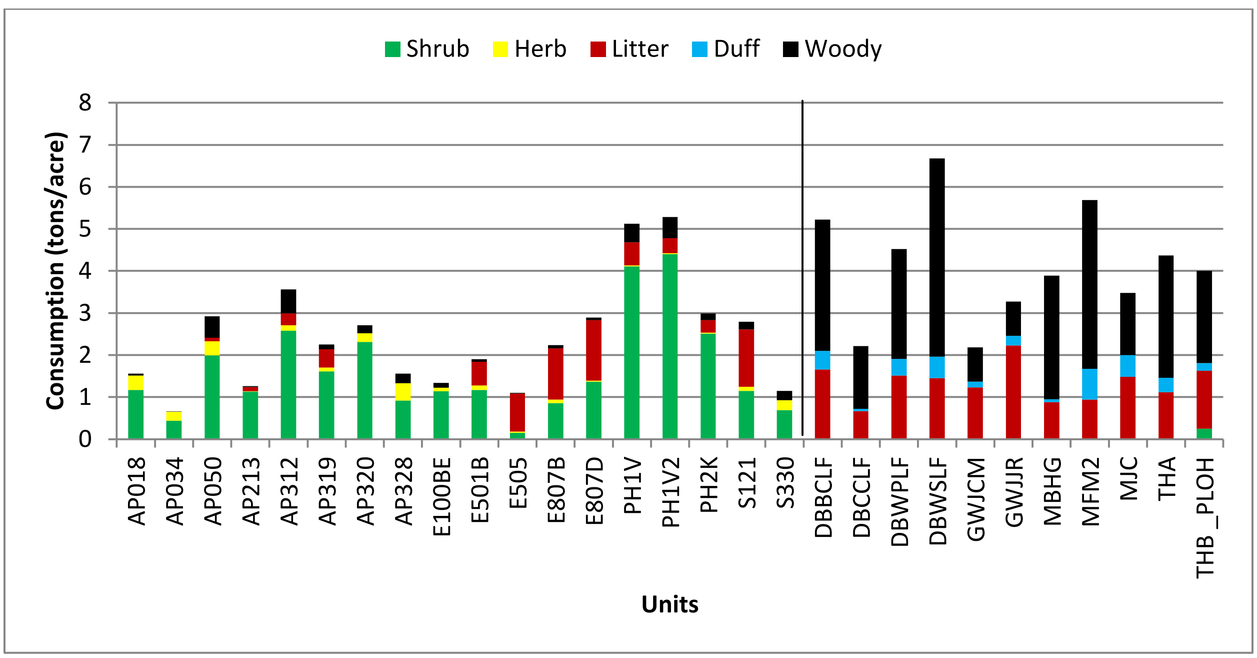


Figure 10. Fuel consumption by fuelbed category. Pine study sites are to the left of the line.

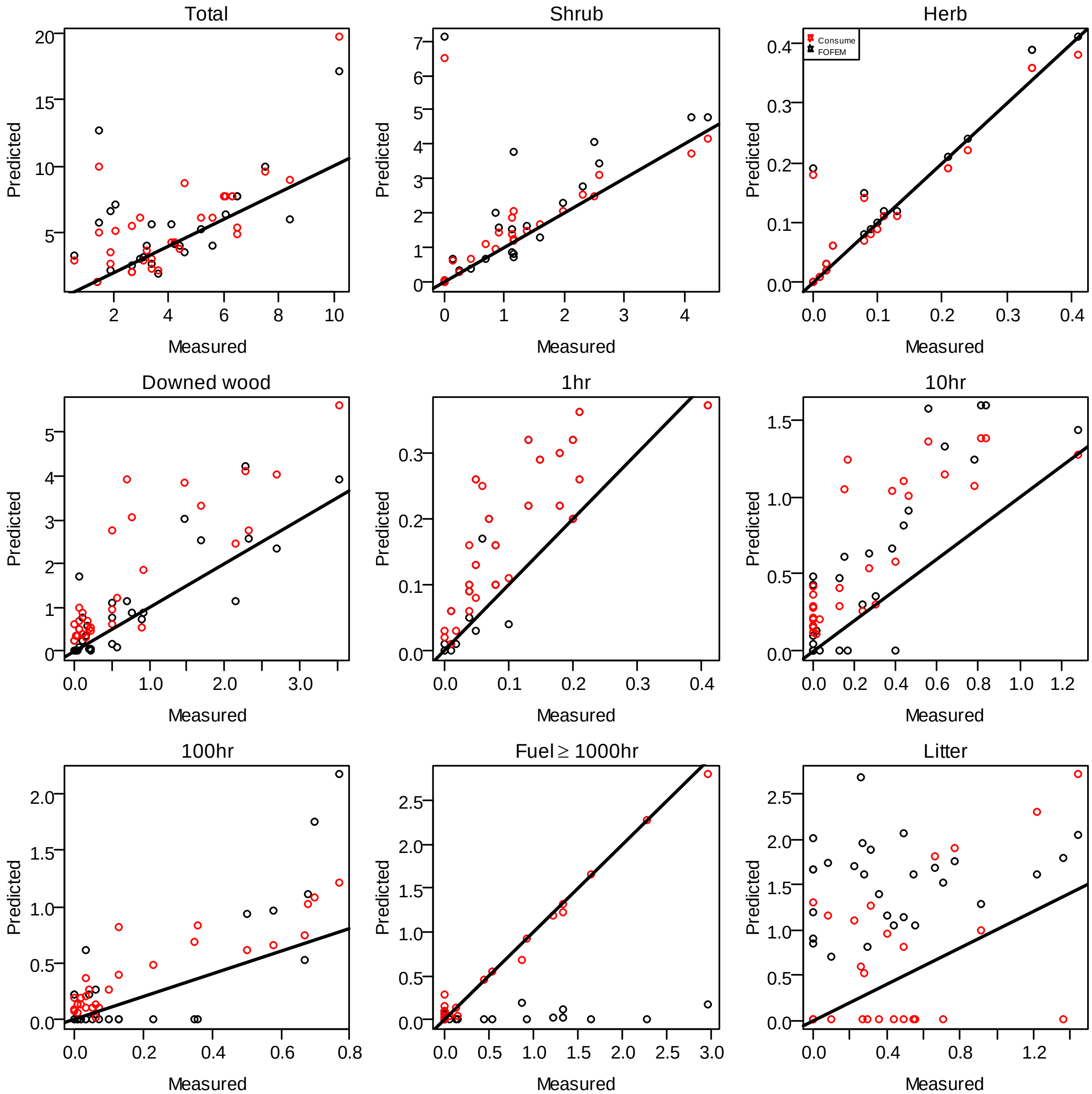


Figure 4: Predicted vs. measured fuel consumption (tons/acre) by total, shrub, herbaceous, all downed wood, 1-hr wood, 10-hr wood, 100-hr wood, ≥ 1000-hr wood, and litter. Red markers represent Consume 4.0 predictions, and black markers represent FOFEM predictions. Black lines represent a 1:1 fit (intercept = 0, slope = 1). Points above and below the black line indicate over-predictions and under-predictions respectively. Plots contain all data points, including model outliers.

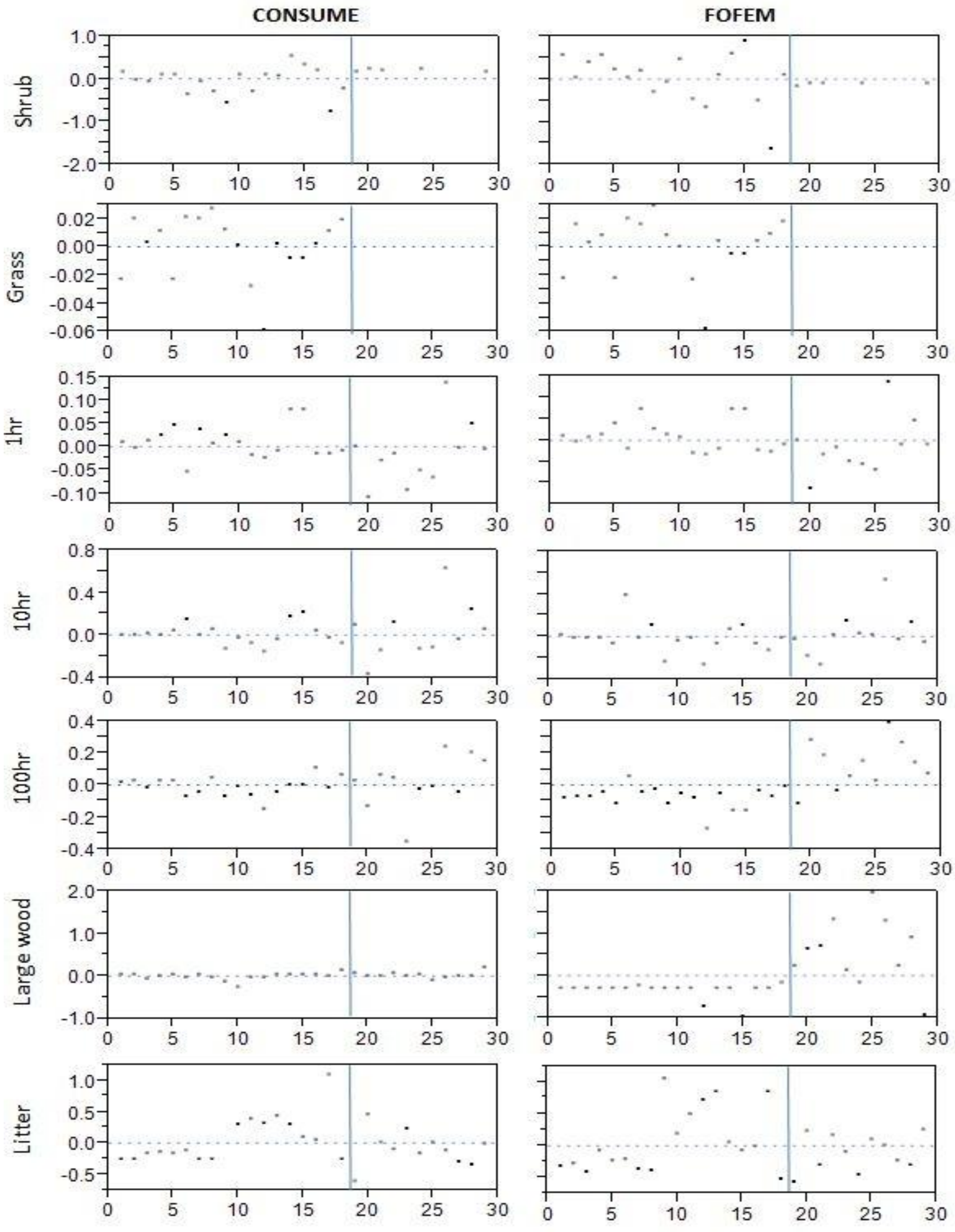


Figure 5: Model residuals by fuel category for Consume and FOFEM predictions. Units to the left of the line (1-18) are southern pine sites and to the right of the line (19-29) are mixed hardwood sites. Y-axis units are differences between predicted and actual fuel consumption (tons/acre).