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Development of decision products for spatial quantification of carbon emissions from wildfire for North America

Final Benchmark Report

June 2011

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Executive Summary

For this recently completed NASA project Michigan Tech Research Institute (MTRI) teamed with specialists at the USDA Forest Service Pacific Northwest Research Center's Fire and Environmental Research Applications (FERA) lab to provide information for mapping fire-derived carbon emissions from historic fires by adapting existing Forest Service fire information products and tools using NASA data and products. This work extends previous research of Dr. French and brings to a wider audience the use of well-established USDA Forest Service models and protocols in the estimation of emissions from wildland fire. The report is organized to present the project plans and results in the context of methodological advances in computing wildland fire emissions at regional to continental scales and in improving access to spatial information used for the emissions modeling.

The Goal of the project is: To provide improved information on carbon emissions from wildfire to users who manage carbon or model the carbon cycle. The objectives are:

- To develop a prototype information system for disseminating and using improved, user-accessible spatial information products for modeling and estimating fire emissions across North America.
- To develop improved products to estimate carbon emissions from North American fires, including fuels maps and fire consumption estimates, based on:
    - NASA-sponsored science and NASA-derived datasets and models; and
    - The adaptation of USFS-FERA information products and models.

Research and development of methods to quantify emissions from wildland fire has come from a variety of communities. Research and tools developed for emissions accounting by the USDA Forest Service (USFS) have been motivated by the need for a full understanding of fire effects on the site to improve methods of smoke management. Regulatory agencies, including the US Environmental Protection Agency (EPA) and state agencies, have been interested in improving methods to account for pollutant and haze-producing events, including wildfire and prescribed burns. Efforts to quantify pyrogenic emissions have been performed at local to landscape scales for quantifying pollutant emissions, in places where data and ground-based information are available; at regional scales, with simplified assumptions regarding fuel type and fuel consumption; or at global scales, whose coarse spatial resolution precludes the highest rigor in model inputs (the use of generalized inputs on fuels and combustion characteristics applicable for broad scales). A comprehensive set of data on fire fuels and consumption, and an approach to estimating emissions at regional scales, will be of great value to land managers who are required to quantify carbon emissions from fire for carbon management.

Prior to this project, dissemination of data on fire emissions consisted primarily of global-scale data sets of fire emissions. Site-specific modeling tools were available for modeling individual fires. These tools require users to collect and input site-specific data, such as burned area and fuel characteristics. Until the WFEIS was developed under this project, access to geospatial emissions estimates at moderate spatial scales (1-km) for regional applications based on user-specified times and locations was not available without extensive resources for geospatial analysis. Spatial data layers describing forest fuels, weather-derived fuel moisture, and methods to define canopy consumption were not fully developed before the project began.

Under the funded NASA project, we have made many advances to improve regional-scale estimates of wildland fire carbon emissions and make these data accessible to the user community. Based on the recommendations of the User Advisory Group, we have developed the web-based WFEIS to address Objective 1, and developed improved input data products and emissions modeling methods to address Objective 2. Outputs include:

- Development of a prototype web-accessible fire emissions calculator API (WFEIS)[1].
- Development of 97 new FCCS fuelbeds[2] for CONUS and Alaska including a doubling of the number of standard fuelbeds for Alaska by the USFS-FERA team.
- Development of a new 1-km resolution map of FCCS standard fuelbeds with fuel loadings for the Continental US and Alaska[3].
- Development of 179 FCCS fuelbed descriptions for Mexico and assistance to Mexican partners in creating a FCCS fuelbed maps for Mexico.
- Translation of the CONSUME 3.0 fuel consumption and emissions equations into a stand-alone Python-based program[4], and for use within WFEIS.
- Translation of the Canadian Fire Weather Index (CFWI) moisture code calculations, a component of the Canadian Fire Behavior Prediction System, into Python[5].
- Ready access to the MODIS-based Direct Broadcast Burn Area Products (DBBAP) for North America for 2001 to 2010 developed by L. Giglio (*Giglio et al.* 2009)[6]
- Access to the emission factors used by the USFS for computing emission components from forest burning[7].

The current version of WFEIS is considered a prototype. Users can estimate emissions from fires across the Contiguous US and Alaska; functionality for Canada and Mexico was not completed, but major strides have been made to allow for this added capability in the future. The intention is to provide access to data sets and results of emissions to provide real estimates for some situations and to demonstrate the capabilities of the system for further development. Further, limited development is happening under new projects, and efforts are in place to find new funding sources to further develop this tool and make it accessible to users.

Contributors to this project and report

In addition to the PI, Co-investigators and Collaborators listed in the title section, the project team included the following research associates and technical experts who worked on various aspects of the project and reporting:

- Benjamin Koziol, MTRI: Co-development of WFEIS geospatial system and data models
- Michael Billmire, MTRI: Integration of geospatial datasets into WFEIS; WFEIS system development support; development of Python-consume
- D. Eric Keefauver, MTRI: WFEIS web site and GUI emissions calculator development
- Mary Ellen Miller, MTRI: Development of fuel moisture estimation methods
- Liza Jenkins, MTRI: WFEIS system testing and generation of WFEIS output
- Susan Prichard, Univ. of Washington: CONSUME development
- Maureen Kennedy, Univ. of Washington: Modeling and programming
- Anne Andreu, Univ. of Washington: Fuelbed building
- Tatiana Loboda, Univ. of Maryland: Fire timing and progression mapping
- Dr. Diego Perez-Salicrup, Universidad Nacional Autonoma de Mexico: Properties of fuelbeds in Mexico
- Prof. Enrique Jardel-Pelaez, Universidad de Guadalajara: Characterization of Mexico's fuelbeds.

[1] http://wfeis.mtri.org
[2] http://www.fs.fed.us/pnw/fera/fccs/
[3] http://www.fs.fed.us/pnw/fera/research/climate/carbon/spatial_carbon_emissions.shtml
[4] http://code.google.com/p/python-consume/
[5] http://code.google.com/p/pyfwi/
[6] ftp://wfeis:fire@ftp.mtri.org/
[7] http://wfeis.mtri.org/media/img/A3-EmissionFactors.pdf

- Jose Maria Michel Fuentes, Universidad de Guadalajara and CONAFOR: Database of Mexico's fuelbed characterization.
- Jorge Morfin-Rios, Universidad Nacional Autonoma de Mexico: Database of Mexico's fuelbed properties and fire regimes.
- Ron Kemker, Jef Cieslinski, Marlene Tyner, Reid Sawtell, Christina Nolte, Peter Gamberg, MTRI: General project support

1. Project Motivation

One of the goals of the North American Carbon Program (NACP) is to resolve uncertainties in understanding and managing the carbon cycle of North America. As carbon modeling tools become more comprehensive and spatially oriented, there is a greater need for accurate datasets to spatially quantify the impact of fire on the carbon cycle, particularly carbon emissions from fire (also referred to as pyrogenic emissions; see for example *Honrath et al.* 2004; *Turquety et al.* 2007). Emissions from fire are globally important, and in some regions represent a significant portion of the carbon transferred from the biosphere to the atmosphere (*van der Werf et al.* 2010). Disturbance by wildland fire is common across North America with most ecosystems in vulnerable to carbon loss through pyrogenic emissions. Wildland fires include lightning or human-caused fires (both accidental and prescribed) in forests, woodlands, shrublands, and grasslands. These fires comprise an important component of global biomass burning emissions. At a continental scale, annual emissions from North American fires vary considerably from year to year due to variability in the amount of burned area in different biomes from year to year as well as variability in fire severity that drives fuel consumption. Each ecoregion of North America experiences its own unique fire conditions and patterns (fire regime). In many areas the fire regime is modified through prescribed fires used for forest management and policies regulating fire suppression. The fire regime also may be changing in response to climate change (*Flannigan et al.* 2005; *Westerling et al.* 2006). This is particularly evident in northern regions where warmer temperatures and longer summer season conditions have resulted in more burning in both the fire adapted boreal forests, where fire has increased (*Podur et al.* 2002; *Kasischke et al.* 2010) or is expected to increase with a warming climate (*Flannigan et al.* 2005; *Amiro et al.* 2009). In tundra, where fires are very rare, several large and extreme events have been observed recently (*Higuera et al.* 2008; *Racine and Jandt* 2008). Across North America, annual burned area has increased over the past four decades as a consequence of increasing fire activity in northern and western forests (*Gillett et al.* 2004; *Kasischke and Turetsky* 2006).

Research and development of methods to quantify emissions from wildland fire has come from a variety of communities. Research and tools developed for emissions accounting by the USDA Forest Service (USFS) have been motivated by the need for a full understanding of fire effects on the site to improve methods of smoke management from both wildfires and prescribed burning. Regulatory agencies, including the US Environmental Protection Agency (EPA) and state agencies, have been interested in improving methods to account for pollutant and haze-producing events, including wildfire and prescribed burns; in some states prescribed burning is closely regulated, with burn quotas and the like, to minimize smoke sources. Agencies and research groups interested in carbon accounting for both carbon cycle science and to better quantify atmospheric inputs of greenhouse gases have developed tools to monitor fire occurrence and emissions. The suite of tools now in place to understand emissions from wildland fire includes the FOFEM, CONSUME[8], and FEPS models from the USFS (*Reinhardt and Dickinson* 2010) developed as on-site tools to assess fire emissions and other fire effects in areas of prescribed fire or wildfire. BlueSky is a spatial smoke modeling framework, also developed by USFS using the FEPS and CONSUME models, to make smoke forecasts and predictions for active fire[9]. FLAMBE'[10] is the US Naval Research Laboratory's method of tracking real-time emissions sources around the globe (*Reid et al.* 2009), and the GFED model also estimates fire emissions globally based on past fire occurrence (currently computed for 1997 to 2009; *van der Werf et al.* 2010). These approaches allow for specific answers to emissions questions and information needs, but a full spatial accounting of fire across North America designed to understand fire emissions at the region scale has not been available until now.

[8] http://www.fs.fed.us/pnw/fera/research/smoke/consume/
[9] http://www.blueskyframework.org/
[10] http://www.nrlmry.navy.mil/flambe/

The components for spatially modeling fire emissions at the continental scale are available due in part to NASA-sponsored research to Dr French and colleagues on remote sensing of fire mapping and characterization, and research on the effects of fire on carbon emissions (*French et al.* 1995; *Kasischke and French* 1995; *Kasischke et al.* 1995; *French et al.* 1996; *Kasischke and French* 1997; *Kasischke et al.* 1999; *French et al.* 2000; *French et al.* 2000; *Kasischke and Stocks* 2000; *French et al.* 2002; *Kasischke et al.* 2002; *Kasischke and Bruhwiler* 2003; *Kasischke et al.* 2003; *French et al.* 2004; *French et al.* 2008), including a recently completed New Investigator Program project by the PI (NASA grant # NNG04GR24G). These data, however, had not been developed into user-accessible datasets and estimates of carbon emissions. Efforts to quantify pyrogenic emissions have been performed at local to landscape scales for quantifying pollutant emissions, in places where data and ground-based information are available; at regional scales, with simplified assumptions regarding fuel type and fuel consumption; or at global scales, whose coarse spatial resolution precludes the highest rigor in model inputs (the use of generalized inputs on fuels and combustion characteristics applicable for broad scales). A comprehensive set of data on fire fuels and consumption, and an approach to estimating emissions at regional scales, will be of great value to land managers who are required to quantify carbon emissions from fire for carbon management.

2. Organization of this Benchmark Report

The report is organized to present the project plans and results in the context of methodological advances in computing wildland fire emissions at regional to continental scales and in improving access to spatial information used for the emissions modeling. First, we present the project goals and objectives along with a review of the potential end user communities in Section 3. The approaches used to execute the NASA-funded project are presented in Section 4. We then review the background of emissions modeling in Section 5. This includes a review of data sets and approaches that have been used to model emissions for a variety of user needs (the baseline before the project start). The final sections (Sections 6 and 7) review the outcomes of the project and the advances made to improve both emissions information and the methods to disseminate these data to the targeted user communities. The benchmarks achieved and outputs created are summarized at the end of the document in Section 8 followed by a set of recommended follow-on activities that would build upon these achievements to make the system more valuable to end user communities.

3. Project Goal, Objectives, and User Community

The intention of the project was to improve on existing data sets to estimate emissions from wildland fire across North America and to make this new data and the methods to spatially apply the data accessible to a broad user base (Appendix A). The overall goal is: To provide improved information on carbon emissions from wildfire to users who manage carbon or model the carbon cycle. The objectives are:

Objective 1: With the assistance of a user advisory group, to develop a prototype information system for disseminating and using improved, user-accessible spatial information products for modeling and estimating fire emissions across North America.

Objective 2: To develop improved products to estimate carbon emissions from North American fires, including fuels maps and fire consumption estimates, based on:

- NASA-sponsored science and NASA-derived datasets and models; and
- The adaptation of USFS-FERA information products and models.

The users targeted for this project were carbon managers, who need to understand the ramifications of fire on the carbon pools they manage, and carbon modelers, who have built or are building systems to quantify and track carbon as it moves through the Earth system, particularly the North American Carbon cycle. The information produced may be of value to other users as well, including management and regulatory groups who have requirements to quantify emissions of pollutants and other atmospheric constituents of interest. These users were considered in development of the prototype information system, but were not the main audience.

To respond effectively to the needs of the user community we formed a User Advisory Group who was charged to:

1. Help define information needs and identify products of interest, including existing data products.
2. Provide input on structure and function of the web-based information system and integration of the new system with existing projects.
3. Proved feedback on initial versions of the system and products during the testing phase to help guide revisions in completion of the final prototype system.

The User Advisory group participants, their relevant expertise, and user category are listed in Appendix B.

4. Project Execution

The NASA-sponsored project began in April 2008 with two research objectives. The Work Plan as revised from feedback from NASA Program Managers based on comments from the review panel is given in Appendix A. The approach to achieving the proposed objectives involved five steps:

1. Coordination of user needs – Obj. 1 & 2
   (user advisory group meeting & surveys)
2. Building the information system – Obj. 1
3. Developing carbon emission information products – Obj. 2
4. Testing the information system & emission products – Obj. 1 & 2
   (feedback from user advisory group)
5. Finalization of the prototype information system & products – Obj. 1 & 2

Specifics of the project activities in years 1 and 2 were summarized in the two annual reports (Appendix C). A list of meetings and outputs for years 1 & 2 are given in the interim reports (Appendix C), and final project outputs are reviewed at the end of this report.

In year 1, emphasis was on developing the plans for building the information system and developing new input data products. The initial activity for the two objectives was to establish the current state of emissions products and data dissemination processes (baseline). One of the first activities was to convene the User Advisor Group to help define user needs and to assist in defining the structure and function of the information system (Task 1 – Coordination of user needs). The meeting was held in Ann Arbor ant the MTRI office on November 5-6, 2008 (Appendix D). Since no previous work has been completed to create a web-based system to create regional-level emissions estimates, we devised a set of starting features and a concept for the information system that was presented at the initial user advisor group meeting (Appendix E). The baseline model inputs and planned products to be developed were compiled in the proposal phase (Table 1) and presented and discussed with the advisory group. The information system features and functionality as well as the input data sets to be used in the new system were based on the baselines and modified from the User Advisor Group discussions and decisions. The new system to be developed was named the Wildland Fire Emissions Information System (WFEIS).

Year 2 activities focused on construction of the WFEIS website and system framework, input data development, and integration of the CONSUME fuel consumption and emissions model into WFEIS; these tasks were completed in the final year of the project. The WFEIS website[11] and interface to WFEIS backend for emissions calculation was developed in the second year and completed in the final year of the project. The opening page provides a very short overview of the system and access to the emissions calculator page and data sets used to estimate emissions across the US. In year 2, the initial functionality of the calculator was developed, and connection of the calculator for building submissions to the web API was put in place. Translation of the CONSUME 3.0 equations into Python (Python-consume[12]) and testing of the code was completed in Year 2; final testing of Python-consume in year 3 allowed us to begin distribution of this code as a stand-alone product several months before the project close (see section 6). Integration of burn area data sets into WFEIS was completed in Year 2.

A preliminary version of the 1-km FCCS map for the US was integrated with WFEIS in the early months of year 2; later in year 2, a revised version of the 1-km map for CONUS was loaded into WFEIS with the Eastern regions and Alaska to come in year 3. Also in year 2, the FERA team developed several new fuelbed descriptions to include in the FCCS. These fuelbeds were included in the revision of the 1-km FCCS map completed in the final year of the project that is now used within WFEIS. Progress in developing Mexican fuelbeds was made in year 2. Mapping fuelbeds for Mexico commenced in the final year, but was not completed before the end of the project.

In the final year of the project, the User Advisor Group was consulted to help review the WFEIS and give feedback. A demonstration of WFIES to the User Advisor Group via Adobe Connect Pro (an on-line meeting system) was conducted on April 18, 2011. Five participants called in to see the demo and all were asked to complete a survey of the system (Appendix F shows the survey; a summary of feedback is given in Section 6 of this report).

5. Previous Emissions Modeling Efforts (Baseline)

Approach to Estimating Carbon Emissions from Wildland Fires

The project completed uses the conceptual methods developed over many years to estimate fire emissions from ground-based data. This approach requires calculation of four parameters as first presented by *Seiler and Crutzen* (1980) and summarized in Figure 1 (*French et al.* 2004): area burned, fuel loading (biomass per unit area), combustion factors (fraction of biomass consumed) for determining fuel consumption, and emission factors (mass of a given chemical species emitted per mass of fuel/biomass consumed). The approach has been refined and emulated for studies at local, regional, and global scales for areas all over the world and a variety of timeframes (*Kasischke et al.* 1995; *Reinhardt et al.* 1997; *French et al.* 2000; *Battye and Battye* 2002; *French et al.* 2002; *Lavoué et al.* 2002; *Kasischke and Bruhwiler* 2003; *French et al.* 2004; *Ito and Penner* 2004; *Kasischke et al.* 2005; *Wiedinmyer et al.* 2006; *Campbell et al.* 2007; *Schultz et al.* 2008; *Joint Fire Science Program* 2009; *Ottmar et al.* 2009;

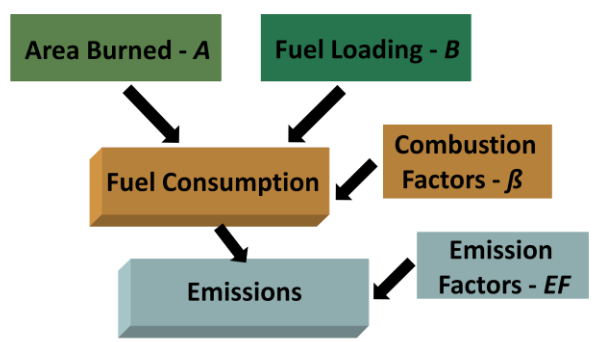

Figure 1: Input data sets needed to compute emissions from wildland fire.

[11] http:\\wfeis.mrti.org
[12] http://code.google.com/p/python-consume

Ottmar et al. 2009). The general equation for computing total carbon emissions (C_t) as interpreted by *French et al.* (2002) and *Kasischke and Bruhwiler* (2003) is:

$$C_t = A \cdot (B \cdot f_c \cdot ß) \qquad (1)$$

where:

A is the area burned (hectares, *ha* or m^2),
B is the biomass density or fuel load ($t\ ha^{-1}$; $kg\ m^{-2}$),
f_c is the fraction of carbon in the biomass (fuel), and
$ß$ is the fraction of biomass consumed in the burn.

The biomass or fuel load (*B, mass per unit area*) is multiplied by the fraction of carbon in the biomass (f_c) to determine the carbon density of the material burned, usually 0.45 to 0.5 for plant biomass pools and a variable fraction for surface organic materials based on the depth and level of decomposition (*French et al.* 2002). The *ß* term is often called the combustion factor, combustion completeness, or burning efficiency (sometimes combustion efficiency, but we reserve this term for emissions partitioning, as explained in the next paragraph). The term is used to capture the variability in the material actually combusted and to determine fuel consumption (the amount of the fuel load removed during a fire). Combustion factors and fuel consumption are known to vary based on fuel type, fuel strata, and fuel condition. In many models combustion factors are determined for each fuel strata and vary due to environmental conditions, especially fuel moisture which is often included as a variable input to emissions models (*Hardy et al.* 2001; *Ottmar et al.* 2009).

Many emissions calculations include estimation of gas and particulate components in addition to total carbon emissions. Most of the carbon released by forest fires is in the form of carbon dioxide (CO_2, ~90% of total emissions), carbon monoxide (CO, ~9%), and methane (CH_4, ~1%) (for a review see *Andreae and Merlet* 2001). Many pollutants emitted from fire are products of incomplete combustion, including carbon monoxide (CO), particulate matter, and hydrocarbons. Combustion efficiency is defined as the fraction of carbon released from fuel combustion in the form of CO_2, with more "efficient" burns releasing proportionally more CO_2 than other compounds containing carbon (*Cofer et al.* 1998). Typically, emissions of a particular gas species or particulate class (E_g) is calculated from C_t using experimentally derived emissions factors (Ef_g), the ratio of a particular gas or particulate size class released to total fuel or carbon burned (e.g., g CO/kg fuel; *Cofer et al.* 1998; *Battye and Battye* 2002; *Kasischke and Bruhwiler* 2003). Typically the amount of carbon dioxide (CO_2), carbon monoxide (CO) and methane (CH_4) released from fires is estimated (*Cofer et al.* 1998; *Kasischke and Bruhwiler* 2003). In estimating the contributions of each gas species, the proportion of flaming, smoldering, and residual burning is defined for each component to account for differences in emission factors for these combustion types. By separating carbon pools and combustion type, these fundamental variables are accounted for and variability of these site-based factors is accounted for. To summarize, the composition of gaseous emissions from a fire depend not only on the amount of fuel consumed, but also on the chemical composition of the fuel and the combustion efficiency for each fuel component.

Site-based to global-scale approaches to estimating carbon emissions from fire have been conducted in many regions and sites within North America. The recently published paper prepared under this grant includes a review of these efforts and a review of recent work to model carbon emissions, including results from a study conducted under this project (*French et al.* 2011). In summary, spatial applications of fire emissions estimation have been minimal. Initial work was done by biome or region (*Seiler and Crutzen* 1980). More recent efforts for broad-scale spatial mapping operate on a gridded format or divide the area of interest into geographically-significant divisions (e.g. *French et al.* 2000 where emissions were computed by ecoregion for the North American boreal forest). Spatial models that operate at landscape (CanFIRE; *de Groot et al.* 2007) and global (FLAMBE', GFED;

Reid et al. 2009; *van der Werf et al.* 2010) scales are in use, but until the WFEIS was developed, no regional-scale spatial approaches that used gridded data inputs had been done.

Accessing and disseminating spatial fire emissions data (Objective 1)

Prior to this project, dissemination of data on fire emissions consisted primarily of global-scale data sets of fire emissions. One such example is GFED v2.1 outputs[13], which were available as monthly outputs in a specific data format as pre-calculated results. Site-specific modeling tools, such as CONSUME 3.0, FOFEM, and FEPS were available for modeling individual fires. These tools require users to collect and input site-specific data, such as burned area and fuel characteristics. Other emissions monitoring tools provide limited data sets, such as FLAMBE' which allows a user to download the global gridded data on fire locations and modeled aerosols or view the spatial data as KML files within Google Earth. MODIS active fire products served out through FIRMS (*Davies et al.* 2009; http://maps.geog.umd.edu/firms/) provide accessible data on fire location, but not emissions.

Until the WFEIS was developed under this project, access to geospatial emissions estimates at moderate spatial scales (1-km) for regional applications based on user-specified times and locations was not available. To obtain the results now available from WFEIS, a user would have had to gather the base data sets, including fire locations, weather, and vegetation fuels, and process these data through a geographic information system, a process that is not feasible for many end users. WFEIS also returns the emissions data in a variety of formats, including text summaries, vector datafiles and raster datafiles.

Data & tools available for spatial estimation of fire emissions (Objective 2)

As part of the project proposal we compiled a list of existing spatial data sets for the factors shown in Figure 1 (Table 1). The WFEIS inputs and emissions estimates are computed at a 1 km spatial resolution, which makes the system outputs relevant for understanding fire-affected carbon cycling at regional scales, and calculations for continental scales feasible. The WFEIS needs to take in the spatial data on fire location, vegetation (fuel), and fire conditions (e.g. weather to define fuel moisture) in order to run the fuel consumption model and determine fire emissions for each spatial location. While the initial intention was to develop these data sets for the entire North American continent, we succeeded in finalizing the data for only the United States. For Mexico and Canada progress has been made, as detailed in the section on project outcomes (section 8 of this report), but a full set of data for these two countries is not yet available. The data sets available at the start of the project to spatially estimate emissions are shown in Table 1 along with the improvements proposed to be completed under the project. This table was included in the original proposal and serves as a baseline list of products along with benchmarks for project Objective 2.

[13] Global Fire Emissions Database (GFED), Version 2.1: http://daac.ornl.gov/VEGETATION/guides/global_fire_emissions_v2.1.html

Table 1: Initial list of information products available at the start of the project, and proposed improvements to be made under the project (from proposal).

Information	*Units*	*Source*	*Description*	*Proposed improvements*
a. Burn area; location	hectare (ha); lat-log	MODIS hot spot products (FIRMS or HMS); MODIS burn area product MCD45	Satellite-based burn area and location products available and under improvement from reliable sources.	None planned
b. Fuel loading (biomass density)	t/ha	USDA Forest Service FERA lab-developed FCCS fuelbeds (http://www.fs.fed.us/pnw/fera/fccs/)	FCCS reports fuel characteristics for each fuelbed stratum based on scientific literature, fuels photo series, fuels data sets, and expert opinion; 50% of NA has completed FCCS characterized fuelbeds.	Develop additional fuelbeds; augment mapping procedure with MODIS products; map FCCS fuelbeds continent-wide. Product comparison with NBCD2000 (http://www.whrc.org)
c. Fuel/ biomass consumption	t/ha	USDA Forest Service FERA lab-developed Consume 3.0 fuel consumption and emissions model (http://www.fs.fed.us/pnw/fera/)	Consume 3.0 uses theoretical models based on empirical data to predict fuel consumption from all material that can potentially burn in a fuelbed; separates the consumption into flaming, smoldering, and residual phases; uses FCCS fuelbeds.	Include Consume 3.0 to the information system for estimating emissions based on FCCS fuelbed. Make small improvements to Consume that make it more applicable to carbon cycle science. Comparison with MTBS
d. Emission factors	$g_{gas}/t_{fuel\ consumed}$	Published in Hardy et al., 2001.	Complete set of emission factors measured from extensive field measurements available for North American fuel types.	No data improvements; Provide ready access to these established data through the information system.

Maps of burn area and timing

Burn area is mapped using fire records and with remote sensing. Fire records have been kept in the US and Canada for decades, and many spatial products have been developed by compiling these records (*Kasischke et al.* 2002; *Stocks et al.* 2002). Products from remote sensing methods are produced by several groups for a variety of purposes, and include both coutry-based maps for the US and Canada and global maps which provide information for Mexico in addition to the US and Canada. Remote sensing products for fire mapping come under one of two general types: 1) burn area based on thermal sensing of hot spots, which are generally active fire products and used for near-real-time applications, and 2) burn area based on algorithms that use more spectral information to map the actual extent of the fire, which are mostly retrospective products for science and management applications that do not require timely information. A review of fire mapping is given in several publications and the techniques are constantly being refined by these and other groups (*Simon et al.* 2004; *Giglio et al.* 2006; *Loboda et al.* 2007; *Roy et al.* 2008; *Giglio et al.* 2009; *Giglio et al.* 2010). Many of these methods were developed for global application, while some are products created for more local and regional applications. Under this project we did not plan to develop new burn area products, rather, to assess what was available for our use from the available products. Table 2 is a list of burn area data sets available for fire emissions mapping in North America this list does not include fire detection products, as they are not as useful for fire area estimation.

Table 2: Burn area products for North America

Product name	Base data source	reference	resolution	geographic coverage	temporal coverage
L3JRC	SPOT VGT	(*Tansey et al.* 2008)	1-km; daily	global	2000 –2007
GLOBCARBON	SPOT VGT & ATSR	(*Plummer et al.* 2006)	1-km; daily	global	1998 –2007
MODIS MCD45A1	MODIS collection 5	(*Roy et al.* 2008)	500-m; daily	global	2002 to present
GFED3 burn area	MODIS, AVHRR, ATSR, TRMM-VIRS	(*Giglio et al.* 2006)	0.5-deg; monthly	global	1997-2009
MTBS burn perimeters	Landsat	(*Eidenshink et al.* 2007)	30-m; annual	US	1984 to present
Canada National Burn Area Composite	AVHRR, MODIS, SPOT VGT, Landsat	(*Li et al.* 2000)	1-km; annual	Canada	1995 to present
US Federal Fire Occurrence Data	Agency records	(*Westerling et al.* 2003)	1-deg; annual	Western US	1980-2008
Alaska Large Fire Database	Agency records	(*Kasischke et al.* 2002)	Variable; annual	Alaska	1950's to present
Canadian National Fire Database	Provincial records	http://cwfis.cfs.nrcan.gc.ca/	variable; annual	Canada	1950's to present

Fuel loading and mapping

Spatial data layers describing forest fuels are necessary for spatially computing fuel consumption and emissions from large wildland fires. Fuel mapping, however, is a difficult and complex process requiring expertise in remotely sensed image analysis and classification, fuels modeling, ecology, geographical information systems, and knowledge-based systems. The high variability of fuels across time and space is a difficult obstacle to mapping of wildland fuels (*Keane et al.* 2001; *Riccardi et al.* 2007; *Sikkink and Keane* 2008). The ecological and technological limitations of estimating fuel quantities directly make fuel classifications for mapping of fuel biomass an effective alternative (*Nadeau et al.* 2005; *McKenzie et al.* 2007; *Lutes et al.* 2009). Many fuel mapping efforts use categories of fuel classifications rather than actual fuel loadings to accommodate the large number of fuel components and spatial variability needed to estimate carbon emissions.

Fuel classifications quantify fuel loads, and therefore carbon pools, by spatially stratifying fuel component loadings by vegetation type, biophysical setting, or fuelbed characteristics. The US Forest Service's Fuel Characteristics Classification System (FCCS) provides a framework for describing fuels in detail. The method uses field-based measures and allometry to calculate the amount of fuel (biomass) in as many as six strata (Figure 2). Development of a moderate-scale (1-km gridded) map using a rule-based approach of standard FCCS fuelbeds and loadings was completed for the contiguous US by the USFS FERA lab prior to this project (*McKenzie et al.* 2007). An advantage of a rule-based classification is that new data layers can be incorporated efficiently because rules only need to be built for new attributes. In addition to this FCCS map, other maps of fuels for the US and for Canada are available, but based on very different fuels description methods (*Keane et al.* 2001; *Nadeau et al.* 2005). The plan for this project was to use the CONUS map of FCCS standard fuelbeds as a starting point. The fuelbeds and the mapping methods were then to be improved to create a more accurate map that included fuels to the north (Canada and Alaska) and south (Mexico).

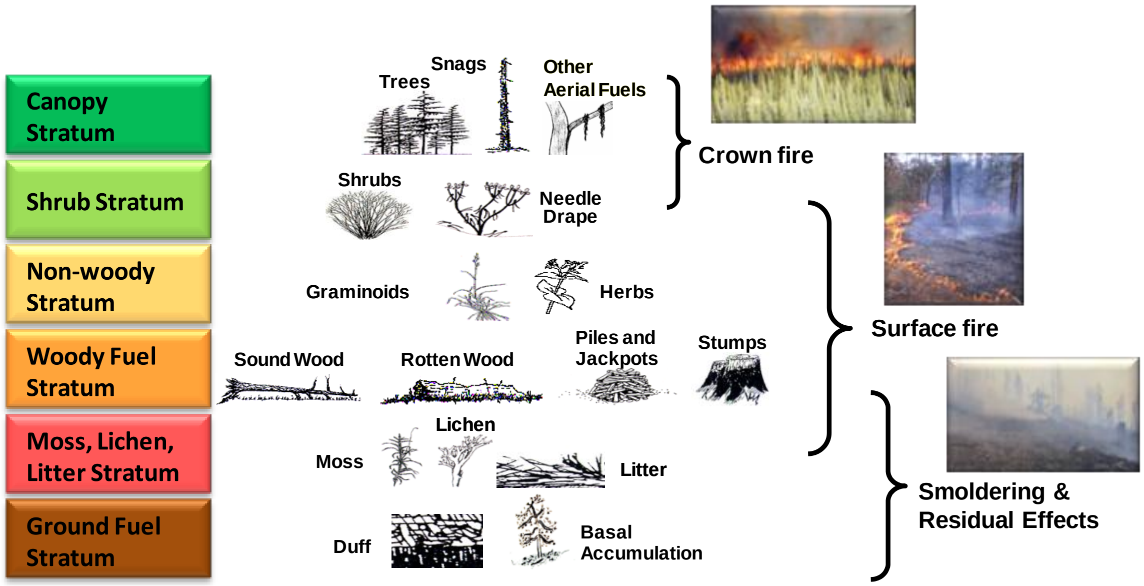

Figure 2: FCCS fuelbed strata, fuel categories in each stratum, and general fire type by strata.

Tools for quantifying fuel consumption & emissions

Site-based to global-scale approaches to estimating carbon emissions from fire have been conducted in many regions and sites within North America using models developed for single studies and for operational use (Table 2).

The project plan was to build from existing models to create a geospatial method of estimating fire within North America. Of the models listed in Table 1, only the GFED global model uses satellite-derived burn area and spatial data on fuels in concert to estimate emissions, but the approach operates at scales appropriate for a global assessment, not regional-scales. CONSUME 3.0 model was used as the starting point for this project with plans to investigate the CanFIRE for Canadian estimates.

The US Forest Service's CONSUME 3.0[14] model predicts fuel consumption and derives emissions of specific gases based on inputs of fuel loads and moistures by fuelbed component. CONSUME 3.0 is a non-spatial model that is accessed through a user-friendly desktop program that can be used to model consumption and emissions based on specific or generalized site conditions (e.g., fuel type, fuel moisture). Combustion is a complex multi-stage process that varies widely among fires and is dependent on fuel type, arrangement of the fuel, condition of the fuel, and in the case of prescribed fires, the way the fire is applied.

CONSUME 3.0 connects directly to the US Forest Service's Fuel Characterization and Classification System (FCCS) fuelbed descriptions, which have been developed to describe fuels and compute fuel loads for approximately 300 fire-affected ecosystem types in the US and Mexico to date (*Ottmar et al.* 2007). Appendix G contains an overview of the CONSUME 3.0 model including its history, characteristics and utility for fire management. Additional details can be found in the CONSUME 3.0 User Guide and other resources available on-line[15].

CanFIRE is a model very similar in basic structure to CONSUME 3.0 developed by the Canadian Forest Service and used for landscape-scale and regional-scale applications (*de Groot et al.* 2007; *Kurz et al.* 2009). The regional-scale application for the FireMARS program, however, does not use

[14] http://www.fs.fed.us/pnw/fera
[15] http://www.fs.fed.us/pnw/fera/research/smoke/consume/index.shtml

full spatial vegetation fuels data. It does, however, use satellite-derived burn area within Canada, making it the closest to the operation of the system planned for our project.

Table 3: Fire emissions models developed for North American and global application.

		Input Source(s)		
Assessment/ model name	***Reference(s)***	***burn area (A)***	***fuel loading method (B)***	***fuel consumption method (β)***
Local to landscape-scale				
CONSUME 3.0	http://www.fs.fed.us/pnw/fera	user defined	user-defined or FCCS (*McKenzie et al.* 2007)	Field-derived relationship to fuel load & moisture
FOFEM 5.7	http://www.fire.org	user defined	User defined as loading or based on fuel class	BURNUP model (*Albini and Reinhardt* 1995)
CanFIRE (BORFIRE)	(*de Groot* 2006; *de Groot* 2010)	user defined	Direct user input values or modeled within CanFIRE from forest inventory	Field-derived relationship to fuel load, fuel moisture (FWI System), and rate of spread
Regional to continental-scale				
Alaska and NA Boreal Forest (BWEM)	(*French et al.* 2002; *Kasischke and Bruhwiler* 2003; *French et al.* 2004)	Alaska LFDB (*Kasischke et al.* 2002)	Field-measured and extrapolated with remote sensing vegetation classes	based on field measures (*Kasischke and Johnstone* 2005)
Canadian FBP System method	(*Amiro et al.* 2001; *de Groot et al.* 2007; *Amiro et al.* 2009; *de Groot et al.* 2009)	Canadian LFDB (*Stocks et al.* 2002)	Canadian FBP System[a] (http://cwfis.cfs.nrcan.gc.ca/en_CA/background/ summary/fbp)	
Canadian FireMARS	*(de Groot et al.*, 2007; *Kurz and Apps* 2006; *Kurz et al.* 2009)	Landsat, VGT and MODIS	CBM-CFS3 (*Kurz et al.* 2009)	CanFIRE, summarized as CBM-CFS3 disturbance matrices
Global-scale				
GFEDv3.1	(*van der Werf et al.*, 2010)	Satellite burn area product	Based on satellite-inputs to CASA	Based on fuel type and moisture in CASA

[a]the Canadian FBP method models consumption as a function of fire weather and fuel type with implicit fuel loadings

6. Project Advances in User Accessible Regional-scale Fire Emissions Modeling

Under the funded NASA project, we have made many advances to improve regional-scale estimates of wildland fire carbon emissions and make these data accessible to the user community. Based on the recommendations of the User Advisory Group, we have developed the web-based WFEIS to address Objective 1, and developed improved input data products and emissions modeling methods to address Objective 2.

The project plan included development of data and accessible modeling methods for all of North America. Our project team includes Bill de Groot of the Canadian Forest Service, who has developed the operational fire emissions model used with the federal carbon accounting program (*de Groot et al.* 2007; *de Groot et al.* 2009; *Kurz et al.* 2009). The team also includes Ernesto Alvarado, who works on the USFS-FERA lab team and has on-going projects in Mexico in collaboration with Mexican researchers and officials. Through both of these project collaborators we have made progress toward developing user-accessible fire emissions estimates that are consistent across the international borders. However, the progress was not enough to include Canada and Mexico in the prototype of the WFEIS (v.0.1). In the first part of this section of the report we review the advances made in data dissemination and model development for the US portion of the project. We then follow these sections with a review of the important advances made to extend these approaches to Mexico and Canada in the last part of this section.

Improving access to fire emissions data sets: Development of the Wildland Fire Emissions Information System (WFEIS)

System attributes and configuration

WFEIS is a internet accessible information system that can be used to estimate emissions from wildfire. An overview of the major components of WFEIS is shown in Figure 2. WFEIS allows for three mechanism of access, which vary in terms of simplicity of use and level of functionality:

1. Web browser access – WFEIS can be access via a web browser at http:/wfeis.mtri.org. This high-level access mechanism is the easiest to use for most users, but only provides a reduced set of the full functionality of WFEIS (i.e. access to fewer burned area datasets, control over burn parameters, etc.)
2. RESTfull API access – WFEIS can be accessed using an Application Programming Interface (API) that allows many software packages allow for HTTP communications. This includes web browsers, but also includes many other types of software packages, such as command line tools, most modern programming languages, and virtual globes (such as Google Earth).
3. Python scripting – WFEIS is built using the Python programming language, and the core algorithms of WFEIS are a collection of Python packages, objects, and methods. The core of WFEIS can be directly accessed using Python as a scripting language. This low-level mechanism allows for the most flexibility in utilizing WFEIS.

WFEIS was constructed from open source components using Python[16], a flexible open source programming language, to tie the components together. WFEIS is built using Django[17], a Python web

[16] Python Programming Language – Official Website: http://python.org/
[17] Django – The Web framework for perfectionists with deadlines: https://www.djangoproject.com/

framework used to create database backed websites. Django can be configured to manage spatial data (a.k.a. GeoDjango[18]) and can connect to relational databases.

WFEIS uses PostGIS[19], an open source spatially-enabled relational database, to store spatial and non-spatial data. The primary spatial datasets are:

- Burned Area Datasets
  - USGS' Monitoring Trends in Burn Severity (MTBS) fire perimeters
  - Direct Broadcast Burned Area Product [TODO: reference Giglio]
  - Fire Progression [TODO: reference Tatiana]
- Fuelbed Maps
  - FCCS Fuelbeds 1km grid (coterminous US and Alaska)
  - FCCS Fuelbeds 30m grid (Southern California only)

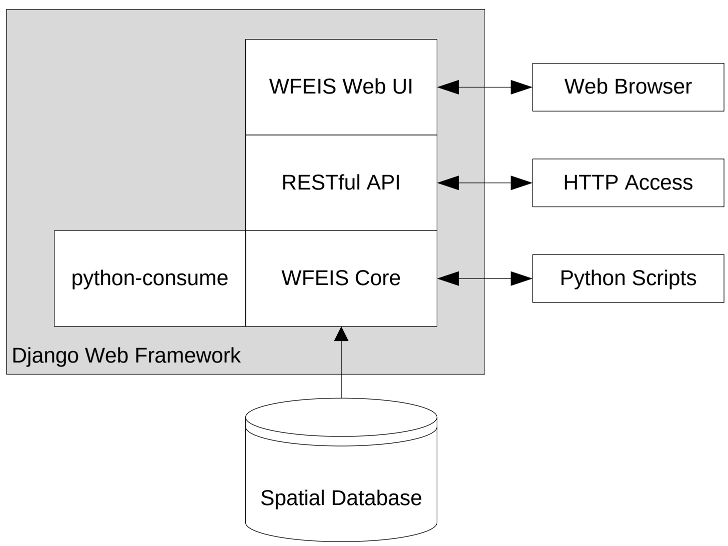

Figure 3: WFEIS system overview

Functionality

In general, users interact with WFEIS by formulating a request for a resource (such as an emissions estimate). WFEIS then processes the user request and responds with a dataset (in a format that was specified by the user). A typical interaction with the WFEIS system proceeds as follows:

1. A user constructs a request (either using a web page or by creating a URL). For example, a request for carbon dioxide emissions from Oregon in 2002 in the KML format would be constructed like:
http://wfeis.mtri.org/api/emissions/fuelbed=fccs1km/burnedarea=mtbs/ecoregion=western/1000hr_FM=None/Duff_FM=None/CanopyPerConsume=None/PercentBlack=50/combustion_stage=total/stratum=total/output_units=kg/emistype=co2/map.kml?DRNG=2002-01-01,2002-12-01&ROI=StateProvince,usa-OR

18 GeoDjango - A world-class geographic web framework: http://geodjango.org
19 PostGIS – http://postgis.refractions.net

2. WFEIS parses the request, and determines which datasets should be requested from the database. For spatial data, processing may occur within the database (i.e. burned area polygons area intersected with fuel map polygons).
3. For fuel consumption and emissions estimates are requested, the data is passed to the python-consume component, which estimates these values. The fuel consumption and/or emissions values are then added to the spatial data.
4. WFEIS then formats the dataset and returns it to the user in whatever format was requested by the user (KML in the example above). WFEIS can return data in a variety of formats, include text files, vector spatial data (i.e. ESRI shapefiles and KML files) and raster spatial data (i.e. netCDF files and GeoTIFF files).

System testing and assessment

The system has been tested to be sure it will run queries with reasonable speed. Input checks (validations) are in place on the calculator page to assure users will be notified if an input is needed and not provided. Feedback from the User Advisors has been compiled (Appendix H) and some of the simpler and more egregious problems fixed. Some suggestions have not been, but can be attended to as we further develop future versions of the system.

Improvements in data and methods for spatial fire emissions: Developing emissions information products for use within WFEIS

Figure 1 summarizes the data sets needed to calculate emissions. For the WFEIS, we have gathered together and, in some cases improved, spatial data on each of the required inputs to calculate emissions on a 1 km grid. Here we review the data and the methods where improvements have been made and are used to compute emissions within the WFEIS. With the exception of some experimental burn progression mapping, no substantial improvements in burn area products were made under this project. We improved usability of the Landsat-MTBS for emissions modeling by creating an improved burn date for the MTBS burn perimeters based on MODIS active fire products, but no modifications to the perimeters were made. We also provide access to the MODIS DBBAP products that are not readily available elsewhere (see link from main page of WFEIS).

Fuels mapping improvements for WFEIS and other regional applications

The 1-km fuels map for the CONUS was entirely rebuilt for this project, and a map for Alaska was built for the first time, reflecting advances in the classification of vegetation and the addition of 97 new fuelbeds to the national FCCS fuels database. These include 20 for the West, 58 for the East, and 19 for Alaska, doubling the number of unique classes from the previous map. The opportunity to use new fuelbeds arose from the availability of the Existing Vegetation Type (EVT) GIS database from LANDFIRE for the CONUS and Alaska, which gives a much more detailed spatial distribution of vegetation than any available previously[20].

A crosswalk was established between EVT and FCCS fuelbeds at 30-m resolution, the native resolution of the Landsat-based EVT. To transform the 30-m FCCS layer to 1 km, we developed a hierarchical aggregation algorithm to optimize the ability of each 1-km cell to represent the fuels in the over 1,000 30-m cells within it. The decision rules for aggregating 30m FCCS Landcover data to 1km data are:

- If the majority (>50%) of 30m FCCS fuelbed cells are of a single category then the 1km FCCS fuelbed cell will be assigned the majority category.

[20] http://www.landfire.gov/

- If there is no majority fuelbed exists among the 30m cells in the 1km cell extent, a majority species is sought.
    - If a species holds a majority within the 1km cell extent, the most common fuelbed associated with the species will be used.
- If no majority species exists, the same logic is followed looking to the covertype, then lifeform-2, and finally lifeform-1 attributes.

The 1-km layer corresponds with the other spatial data in WFEIS, and also with the spatial resolution of regional climate models, air-quality models, and dynamic global vegetation models (Appendix I). The 1-km fuels map is linked within WFEIS to a lookup table within the emissions model that informs fuel loadings values and consumption parameters for 5 strata and associated substrata (Figure 2) for computing fuel consumption.

Fuel consumption: Implementation of CONSUME within WFEIS

The CONSUME model was developed by the USFS FERA lab based on field measures of consumption and emissions. The model uses empirical relationships between fire conditions (fuel type and moisture) and fuel consumption to predict emissions. CONSUME 3.0 (the most recent version of the systems, which includes a GUI interface to the models) was developed as a planning and fire management tool and has been adapted for this NASA project to operate in a spatial context within the WFEIS. Within WFEIS, the model uses fire location and timing to define the fuel type and weather conditions. CONSUME connects directly to the FCCS fuelbed data and computes consumption and emissions by strata and combustion stage (Figure 2; see Appendix G).

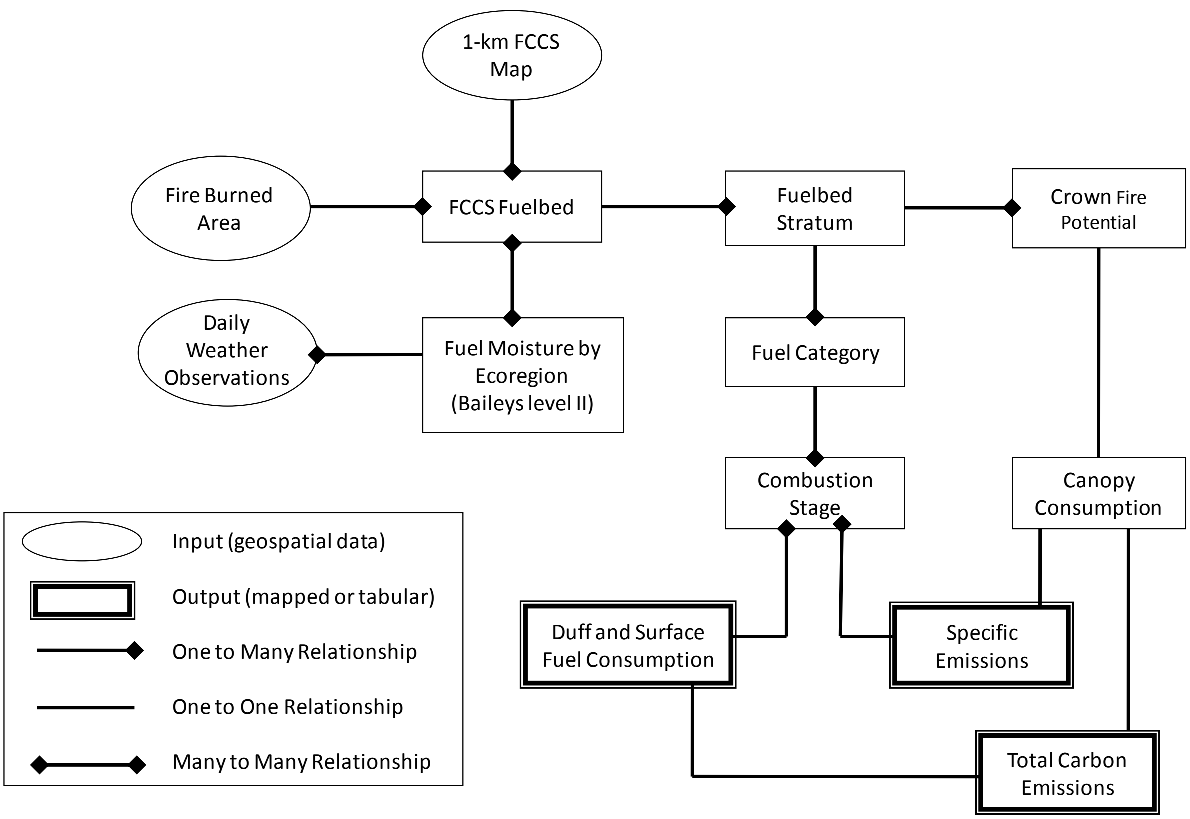

Figure 4: Simplified schematic of the CONSUME model as used within WFEIS and connection to the FCCS 1-km map.

Development of Python-consume

To facilitate the integration of CONSUME 3.0 functionality into WFEIS, it was decided that the equations for fuel consumption and emissions be recoded into Python programming language. Python is a flexible open source object-oriented programming language that underlies the Django web framework used by WFEIS. Python-consume was coded utilizing the Consume 3.0 User's Guide, the original source code (provided by the original developers), and frequent consultation with original developers Susan Pichard and Roger Ottmar (USDA FS FERA). Python-consume was robustly tested against the official CONSUME 3.0 to ensure compatibility, although results will not always align due to several errors discovered in the original source code.

The primary purpose of Python-consume was to integrate with WFEIS. This means that it was coded primarily for batch processing to have the infrastructure and flexibility to handle very large and redundant input datasets. Coding for WFEIS also meant that the fuel loading and emission factor information was derived entirely from FCCS data (and not SRM/SAF cover types as is available in the CONSUME 3.0 version). Additionally, there was a reduced emphasis on GUI development as user interaction is handled by the WFEIS front-end "Emissions Calculator" form. Finally, there was an emphasis on “natural” as opposed “activity” consumption equations (although the "activity" equations were later added).

Python-consume is currently hosted as a Mercurial repository on Google Code[21] to make it accessible to the user community and is administered by MTRI and USDA FS FERA. A link to the repository can be found on the WFEIS web site.

Python-consume fuel-related inputs

CONSUME was developed to connect directly to the FCCS system by taking in FCCS-derived fuels variables required for the CONSUME calculations. This includes fuel loadings by strata as well as the FCCS-defined crown fire potential that is used to define percent canopy consumption within the WFEIS implementation of CONSUME. Fuel loadings for each stratum are computed for each fuelbed in the FCCS 1-km map using the methods developed within the FCCS systems (*Ottmar et al.* 2007). These loadings are included for each fuelbed strata within WFEIS as a look-up table for access by Python-consume based on the FCCS fuelbed code in the area burned. Because fuels can vary across an area burned, loadings will also vary across an area burned.

WFEIS uses the crown fire potential defined for each standard fuelbed to decide on the percent of canopy consumption to input into Python-consume. In the original CONSUME 3.0 system, canopy consumption is a user-defined input. In the case of WFEIS, Python-consume requires a value for percent canopy consumption to be defined without user interaction. Each FCCS fuelbed contains information to calculate the Crown Fire Potential, which is the weighted average of three crown fire sub-potentials. The three sub-potentials are: Crown Fire Initiation Potential (CFIP), the potential for fire to reach canopy layer; Crown to Crown Transmissivity (C2CT), the potential for fire to carry through the canopy; and Crown Fire Spreading Potential (CFSP), a relative index of crown fire rate of spread. WFEIS uses an integrated assessment of the subpotentials to calculate the % canopy consumption as follows:

- if the CFIP is low (less than or equal to 3) then the Canopy Consumption % input to Python-consume is zero.
- If the CFIP is greater than 3, then canopy consumption percentage is calculated based upon the following equation:

  Canopy Consumption % = [(C2CT*0.5)+(CFSP*0.5)]*10

[21] http://code.google.com/p/python-consume/

Shrub Blackened is one of the inputs required in Python-consume. The variable is a description of the percent of the shrubs in the area burned that are impacted by the fire. The variable only impacts fuelbeds that have a shrub component. In CONSUME 3.0, this value is a user-defined input with the default set at zero. Within Python-consume, the shrub blackened input is set to 50%. With little research on the drivers of the variable, we decided to leave the input constant in the prototype version. Users are able to modify this input, but it will be always set the same across all burned areas in the query, as long as the fuelbed has a shrub component.

Fuel moisture inputs

CONSUME requires two measures of fuel moisture to compute consumption and emissions, 1000-hr fuel moisture from the National Fire Danger Rating System (NFDRS) and duff moisture as a percentage by volume. For the original application of CONSUME these variables were input by the user for the situation being modeled. Because of the spatial nature of WFEIS and the need to have fuel conditions information for any place or time of a fire, these inputs have been developed for WFEIS as a spatial-temporal data layer. To minimize the spatial complexity of a WFEIS query, in the prototype version of WFEIS we map the two fuel moisture variables as a function of ecoregion using Baileys Ecoregion level 2, to match with the ecoregion divisions used within CONSUME to designate the equation set to use (see above). Fuel moistures are computed daily for each ecoregion, as explained here.

National Fire Danger Rating thousand hour fuel moisture for WFEIS
The NFDRS was developed to measure and predict fire danger and potential on a national scale. Fuel moisture is an important predictor of fire behavior and effects. Initially fuel moisture content was measured using fuel rods, but these measurements have been replaced with empirical relationships derived between weather data and live and dead fuel moistures (*Fosberg et al.* 1981). Dead fuels are classified into different sizes that correspond to the length of time (known as the lag time) it takes these fuels to gain or lose 63% of their initial moisture content. Thousand-hour (1000-hr) fuels are dead plant material having a diameter range of 7.6 to 20 cm; they are the largest fuels in the NFDRS and have the longest lag time (*Deeming et al.* 1978). Therefore they respond slowly to changes in atmospheric moisture. NFDRS 1000-hr fuels are routinely used to predict fire behavior, but are also useful in predicting fire effects in models such as FOFEM (First Order Fire Effects Model) and CONSUME.

Daily NFDRS 1000-hr fuel moisture values are estimated empirically from weather data for the previous seven days and the initial 1000-hr fuel moisture content (*Ottmar and Sandberg* 1985). The empirical estimate uses daily minimum and maximum temperature, daily minimum and maximum relative humidity, the duration of any precipitation events, and solar insolation. Solar insolation is estimated using station latitude. Ideally weather data used in these estimates include daily minimum and maximum temperature and relative humidity and precipitation duration. Weather data for the NFDRS are collected for over 2000 Remote Automatic Weather System (RAWS) fire weather stations located across the U.S. (http://raws.fam.nwcg.gov/ [Verified 1 June, 2011]). Occasionally stations are missing required observations; however in some cases the missing data can be estimated. Depending on location these stations gather data year round or during the fire season. Additionally transient stations are available for deployment in order to monitor conditions near large fires.

Because calculated fuel moistures are not archived by the USFS, the NFDRS 1000-hr fuel moistures had to be recalculated in order to obtain historical fuel moisture maps for the CONSUME model within WFEIS. The archived RAWS weather station data was downloaded from the National Fire and Aviation Management Fire and Weather data site[22]. Historical NFDRS 1000-hr fuel moistures were determined using equations found in (*Cohen and Deeming* 1985) and from code used in Fire

[22] http://fam.nwcg.gov/fam-web/weatherfirecd/index.htm

Family Plus (*L. Bradshaw, USDA Forest Service*, pers. comm. 2011). As our values were generated using the same algorithms used by the Forest Service, they are subject to the same weaknesses, for instance stations that gather data seasonally need roughly a month before fuel moisture values are reasonable. This is caused by the need for a boundary condition of an initial 1000-hour fuel moisture that must be estimated. Fuel moistures for all stations with data after 1982 were processed to be used for determining daily fuel moisture on an ecoregion scale. Currently the WFEIS database of NFDRS 1000-hr fuel moistures contains 2,138 stations with over 8 million daily records.

Daily 1000-hr fuel moisture interpolations used a block kriging method to generate best estimates of fuel moisture at the ecoregion level (Baileys level II)[23]. Block kriging is a geostatistical technique used in cases where an areal estimate for a region is preferred over the more commonly used point-based interpolation (*Goovaerts* 1997). Blocks (in this case the blocks are equivalent to polygon representations of ecoregion boundaries) are delineated and a discretization grid chosen. The grid is a tessellation of regularly spaced points at which the response variable (fuel moisture) is estimated then summarized over the block. A 100-km grid spacing is used in WFEIS which ideally captures the spatial variability of landscape fuel moisture while also minimizing the computations required for geostatistical estimation.

Block kriging, like other geostatistical methods, requires a model of the spatial correlation of the response variable (i.e. variogram) to calculate observation weights and generate estimation uncertainties. Monthly variograms (12 different forms total) were fit from the observational data. These variograms took the form of a power model with an increasing linear covariance as the distance between observations grew larger. Variogram models were combined with spatiotemporal data on station locations and date-specific fuel moistures using a Python package containing geostatistical routines interfacing directly with a PostGIS spatial database. The final results of the interpolations are daily 1000-hr fuel moisture estimates with confidence intervals for each ecoregion designation.

Computing duff moisture for WFEIS

The loosely compacted decomposing organic material on the surface of the soil layer in forested ecosystems is also called duff. It is composed of partially to fully decomposed litter and moss varying based on the ecosystem type and decomposition rates at the site. The moisture of the duff is an important driver of duff consumption and fire emissions because the amount of water in the material has strong influence on the thermodynamics of the fire and the characteristics of the combustion. The CONSUME model requires an input of duff moisture, expressed in percent, with the empirical relationships used to compute consumption and emissions from the ground fuels strata.

As with the 1000-hr fuel moisture variable, duff moisture is included within WFEIS as a spatial data layer which changes daily and is spatially aggregated to ecoregion. In the WFEIS system, duff fuel moisture is calculated from the Canadian Fire Weather Index Duff Moisture Code (DMC) in order to estimate the input based on spatial weather data according to the following equations from *Lawson et al.* (1997):

Duff Fuel Moisture % for Lower 48

$$\%\mathrm{DM} = \mathrm{e}^{\left[\frac{\mathrm{DMC}-244.7}{-43.4}\right]+20}$$

Duff Fuel Moisture % for Alaska

$$\%DM = e^{\left[\frac{DMC-149.6}{-20.9}\right]}$$

[23] http://www.nationalatlas.gov/mld/ecoregp.html

The DMC is a numerical rating of the fuel moisture in shallow to medium, loosely compacted duff at a depth of 10-20cm, and in medium weight surface fuels (*Van Wagner* 1987). In WFEIS the DMC is derived from the North American Regional Reanalysis (NARR)[24] weather data and calculated using the Canadian Fire Weather Index (FWI) System. The DMC is calculated from specific measured parameters: temperature, relative humidity, rain, and windspeed, as well as the previous day's DMC, month the measurement was made, and latitude. The Canadian Forest Service provided us with the tools to compute the DMC and the other indices included in the FWI system from these parameters. From this tool, we created a Python version of the Canadian FWI which is available via our web site. A spring initiation DMC value is necessary to compute subsequent days' DMC values. Since the start day each year is difficult to define systematically, we ran the FWI continuously starting in mid-1999. We performed an analysis to determine if this was an appropriate approach to be sure the equations were stable over long periods of time, which they were. As with 1000-hr fuel moisture, daily estimates of duff moisture were calculated and aggregated to the ecoregion level (Baileys level II).

Improved access to emission factors

Emission Factors, in the case of biomass burning, are used to estimate specific components of smoke based on the amount of fuel consumed. Usually, the units are kg-X/kg-dry-fuel (or equivalent English metrics), where X is the gas or component of interest. These factors have been experimentally developed for many smoke constituents of interest, and in the case of CONSUME and WFEIS include particulate matter ($PM_{2.5}$ and PM_{10}), CO_2, CO, CH_4, and non-methane hydrocarbons (NMHC; Appendix J) (*Ward and Hardy* 1989; *Hardy et al.* 1998). These emission factors are available from the literature, and are now more easily accessed through the WFEIS web site. They are also integrated with the CanFIRE model, allowing estimation of these smoke constituents by that method.

Advances in mapping emissions in Mexico and Canada

The proposed improvements to regional-scale emissions modeling capability included development of data sets to compute emissions across North America. It was obvious from the start that this task would be easiest in the US because of existing data sets and emissions model and the engagement of USFS FERA lab personnel. While the final prototype WFEIS developed does not include ability to map emissions outside of the US, many key advances were made with our Mexican and Canadian partners to eventually develop continent-wide capabilities, as planned.

Mexico

Fire has become a high priority for ecosystem management in Mexico. However, current fire management practices are still centered on the fire suppression paradigm that has produced a health decline of the ecosystems in western North America. Mexican government is implementing new conservation and management policies that steer away from fire suppression. These new policies require sounder information for developing land management practices adapted to the ecological and social conditions of Mexican forests. The timing of the NASA funding was appropriate for connecting with similar efforts by the Mexican National Forestry Commission (CONAFOR).

It became obvious in the early stages of the project the challenges that we would face to complete the Mexico part of the project. Mexico lacks of a fuel characterization system that represents the complexity and diversity of one of the most Mega-diverse countries in the world. There have been attempts to use the US and Canadian fuel and fire systems in Mexico to no avail. During the implementation of the project, we found that there is sparse data in published and grey literature but it is not consolidated in a single place and not readily accessible. A major achievement of this project

[24] http://www.emc.ncep.noaa.gov/mmb/rreanl/

was to create a synergy with Mexico's own interest to improve the fire management system based on information that consistently represents their ecosystems and fire environments.

At the beginning of the NASA funded project, Mexico did not have a fuel characterization and smoke emission system. At the end of our funding, Mexico continues developing its own fuelbeds and management tools. It became a task that goes beyond the NASA funding period. Nevertheless, in the near future it will produce a system fully compatible with the system completed by this project for the United States.

The initial Mexican fuelbeds developed for the project are based on the FCCS approach. It uses the most recent Mexico's Vegetation Serie IV, fire regime classification, and fuels data that has been collected from different sources, and in the future will include fuel data collected by the National Forest Inventory (Appendix K-1). The current fuelbeds developed for Mexico includes 179 that represent most of the major ecosystems of Mexico. The information in the current database includes the author and location of the fuels data, state, associated INEGI vegetation type Serie IV, and fuel characteristics. The Appendix K-1 includes a summary of the 179 fuelbeds developed for the project. They have not been mapped because incompatibilities between Mexico's vegetation mapping system and the LANDFIRE system used for FCCS mapping in the United States. Another source of initial incompatibility was the different usage of Imperial units in FCCS and the desire of the Mexican government to keep International Units for their system. The difference in measuring units has been solved recently but not on time to incorporate the Mexico data into the FCCS.

The NASA funded project was introduced to Mexico's National Forestry Commission (CONAFOR). CONAFOR adopted the idea behind this project and decided to support it by funding a team of Mexican scientists to counterpart the NASA project. CONAFOR funded two projects to Mexican scientists to develop applied tools that can be used for fire management and improving the CO_2 reporting system for REDD+ commitment to IPCC. The lack of a fuelbed database and the interest of Mexico in developing their own fuel database changed the pace of the project execution. We were working together with the Mexican team to develop a fuel database.

The two CONAFOR projects were awarded to the National Autonomous University of Mexico (UNAM) and University of Guadalajara (UG). The NASA funds partially supported the collaboration of a University of Washington faculty (Alvarado) and partially covered the visit of two of the Mexican scientists to the USFS Seattle Fire Laboratory and the University of Washington in Seattle (Peres-Salicrup and Michel-Fuentes). These two projects still continue in Mexico.

The goal of the first CONAFOR project is to develop a database of fuelbed physical properties for forest ecosystems of Mexico. The second project goal is to develop a map and database of fire regimes and fuels for Mexico's major forest ecosystems. Two of the progress reports of those projects are included in Appendix K-2:

- Physical Fuel Properties of Forest Fuels in Forest Ecosystems of Mexico
- Characterization, Classification and Mapping of Fire Regimes in Forest Ecosystems of Mexico.

One of the main sources of field data for the fuelbeds was the Mexico Photo Series (*Alvarado Celestino et al.* 2008) that covers natural protected areas in western and Northern Mexico. There is sparse fuel data in Mexico, but much of it not fully compatible with FCCS. Due to the lack of consistent fuels data for most of Mexico data, CONAFOR sponsored the development of a manual to evaluate and quantify forest fuels, requiring that it should be compatible with forest the FCCS (Appendix K-3). These protocols have been incorporated in the National Forest Inventory field protocols. Fuels are now consistently collected at a national level. This fuel database will be used to improve and expand the initial fuelbeds developed by this NASA project. The timeframe for the data analysis of the National Forest Inventory just started and will go on for another couple of years.

Fires in tropical ecosystems are a concern of Mexico because of the threat of increasing fire due to land use change and climate change. A major challenge faced by any forest fuel system is the characterization of tropical ecosystems. For the first time in fuel modeling, this NASA project was able to sponsor the development of a system to characterize fuelbeds in tropical forests and savannas. The system is based on the FCCS and it was tested at the Selva Zoque in Chiapas. The initial catalog of tropical fuelbeds is included in Appendix K-4. The catalog of tropical fuelbeds includes humid tropical forest, dry tropical forest, and savannas. Similar process can be replicated in other tropical systems of Mexico or elsewhere. Future tropical fuelbeds that will be developed from the National Forest Inventory will follow the framework described in Appendix K-4.

A unique characteristic of the Mexico's fuelbeds is that they are directly linked to fire regimes. The schematics of this relation are included in Appendix K-5. In Appendix K-5, there is also an initial map of hypothetical fire regimes for Mexico's terrestrial ecosystems, which it will be used as an input to map Mexico fuelbeds. A task that is pending and will be completed by collaborators in Mexico and the University of Washington is a crosswalk between the LANDFIRE mapping approach, which is used to map FCCS in the United States and Mexico's own INEGI Vegetation Type Serie IV.

A milestone that was accomplished by the partnership developed with CONAFOR and our Mexican collaborators at UNAM and UG, is an improved report on fire emissions that was included in the country report for IPCC. The report was completed in 2009. The fire emissions report is based on the initial Mexico's FCCS fuelbeds and CONSUME. The report was integrated in the emissions report from Mexico to IPCC. A copy of the report is included in Appendix K-6. The fire emissions report includes area burned, pre-fire biomass, fuel consumption and fire emissions by vegetation type (INEGI Serie IV).

An ongoing project in CONAFOR is to review and improve the current approach thatthat is used for Mexico's Quarterly Report of CO_2 Emissions from Wildfires. The quarterly report is being reviewed by CONAFOR with the assistance from the US Forest Service and the University of Washington. The approach foo reviewing this quarterly report will be based on the protocols and work initiated by the NASA project and the two projects funded by CONAFOR.

Although our project was not able to complete an implementation of WFEIS for Mexico, it initiated a process that will produce a fuel characterization system for Mexico and improve the fire emissions for REDD+ reporting system. The NASA project also fostered the initiation of research projects in Mexico funded by CONAFOR and CONACYT that will produce in the near future a national map of fuelbeds that will be used for emissions and improvement of fire management policies.

Canada

Canada has developed some of the world's most sophisticated methods and tools for fire management and monitoring as well as in characterizing the forest carbon budget. The Canadian Forest Service (CFS) has developed an operational-scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; *Kurz et al.* 2009)[25] which is a comprehensive assessment of the carbon state and function of the forests in Canada, including emissions of carbon from fire. The fire emissions model used within CBM-CFS3 is CanFIRE, a refinement of the BORFIRE model (*de Groot* 2006; *de Groot et al.* 2007; *de Groot et al.* 2009). CanFIRE uses the same basic approach as CONSUME to estimate fuel consumption and carbon emissions by using fuel load and fuel moisture parameters. Both CONSUME and CanFIRE are empirically-based models, but derived from different field datasets. The intention for our project was to consider how CanFIRE and CONSUME, which was to be used as the basis for emission modeling for the US and Mexico, compare in their model inputs and results, and then decide with Dr de Groot and others involved in Canadian carbon modeling how best to create a continent-wide system that was seamless across international borders.

[25] http://carbon.cfs.nrcan.gc.ca/CBM-CFS3_e.html

A model comparison was completed under this project and published (*French et al.* 2011; Appendix L). The results show that the models do compare favorably. More "head-to-head" comparisons are planned, to assess some of the specific model assumptions. For example, the CanFIRE model has a much more rigorous method of computing canopy consumption and emissions from crown fires than CONSUME, which relies on an un-tested formula (see Next Steps section). On the other hand, CONSUME has a much wider range of fuel types (e.g. shrublands and diverse western forests) than CanFIRE, which was originally designed for boreal forests. Direct comparisons of the models in more sites and at the regional scale will help understand the magnitude of these differences and improve both models.

The basic concepts employed by CanFIRE to calculate emissions are fundamentally the same as those used by CONSUME. However, the algorithms for calculating fire behavior and fuel consumption are based on Canadian experimental and wildfire data. In brief, CanFIRE calculates consumption in three distinct fuel components: forest floor (representing L, F and H organic soil layers), dead and downed woody debris (5 size classes), and aerial (aboveground live tree) fuels. CanFIRE is used to calculate annual national wildland fire carbon emissions (*de Groot et al.* 2007), which is now operationally referred to as the Fire and Carbon Emissions Monitoring, Accounting and Reporting System (FireMARS), for international reporting under the National Forest Carbon Monitoring, Accounting, and Reporting System (NFCMARS) (*Kurz and Apps* 2006). Currently, the Canadian Government uses a semi-spatial method with FireMARS to estimate forest fire emissions.

One problem in reconciling the Canadian approach with the US approach is the lack of national fuels maps for Canada that are equivalent in detail as the database with FCCS fuelbeds in the US. CanFIRE is able to operate on multiple strata, as CONSUME does, but site-specific data on fuel loads is required. The only nation-wide maps of fuels for Canada are based on the Canadian FBP system fuel types, which are not comprehensive fuels descriptions and do not include fuel loadings. To run CanFIRE in Canada, stand level fuels data is usually derived or interpreted from forest inventory. Although national fuel type and fuel load maps for Canada were not produced under this project, there have been discussions with CFS personnel on how these types of spatial databases may be created for Canada. These discussions are on-going, so new fuels data may be developed in the near future for use in spatial emissions modeling. One possible outcome of the discussions started under this NASA project with the CFS is development of datasets and procedures to model emissions across North America using either CanFIRE or CONSUME as two comparative estimates, and served out through the MTRI WFEIS web site.

7. Project Outcomes

Improved information for estimating fire emissions

The NASA-sponsored project has resulted in an array of improvements to regional-scale estimation of fire emissions and to access to data and emissions estimates by the user community. Outputs include:

- Development of a prototype web-accessible emissions calculator API (WFEIS)[26] to make computationally efficient, on-demand estimates of daily fire emissions for any location within CONUS and Alaska for time periods within 1983 to 2009.
- Development of 97 new FCCS fuelbeds[27] for CONUS and Alaska including a doubling of the number of standard fuelbeds for Alaska by the USFS-FERA team.

[26] http://wfeis.mtri.org
[27] http://www.fs.fed.us/pnw/fera/fccs/

- Development of a new 1-km resolution map of FCCS standard fuelbeds with fuel loadings for the Continental US and Alaska[28].
- Development of 179 FCCS fuelbed descriptions for Mexico and assistance to Mexican partners in creating a FCCS fuelbed maps for Mexico.
- Translation of the CONSUME 3.0 fuel consumption and emissions equations into a stand-alone Python-based program[29], and for use within WFEIS.
- Translation of the Canadian Fire Weather Index (CFWI) moisture code calculations, a component of the Canadian Fire Behavior Prediction System, into Python[30].
- Ready access to the MODIS-based Direct Broadcast Burn Area Products (DBBAP) for North America for 2001 to 2010 developed by L. Giglio (*Giglio et al.* 2009)[31]
- Access to the emission factors used by the USFS for computing emission components from forest burning[32].

Presentations & Publications

The following presentations were made during the course of the project (many of these are available on the project web site[33]). Recently, we have demonstrated the WFEIS to several interested parties via Adobe Connect Pro, a web-based meeting forum. Plans are to record the demo for posting on the WEFIS web site. We have published one paper from the research and have two papers planned.

2008

- Nov: Presentation of project to Canadian Forest Service and others in Victoria, BC

2009

- May: Oral presentation at the Spring AGU, Toronto, Canada
- Nov: Poster presentation at the 4th International Fire Ecology & Management Congress
- Publication of article on WFEIS in Canadian Smoke magazine

2010

- Mar: Poster presentation at NASA Terrestrial Ecology Program meeting, La Jolla, CA
- Oct: Oral presentation at Wildland Fire Canada 2010, Kitchener, Ontario, Canada
- Dec: Poster presentation of project at Fall AGU, Dec. 2010

2011

- Feb: Poster presentation of results of comparison study at North American Carbon Program All Investigators meeting.
- Mar: WFEIS demo to USFS-FERA team and visitors

[28] http://www.fs.fed.us/pnw/fera/research/climate/carbon/spatial_carbon_emissions.shtml
[29] http://code.google.com/p/python-consume/
[30] http://code.google.com/p/pyfwi/
[31] ftp://wfeis:fire@ftp.mtri.org/
[32] http://wfeis.mtri.org/media/img/A3-EmissionFactors.pdf
[33] http://wfeis.mtri.org/projout

- Apr: WFEIS demo to User Advisory Group
- Jun: WFEIS demo to Canadian Forest Service FireMARS team
- Paper published comparing WFEIS to other emissions models at specific sites (*French et al.* 2011; Appendix L)

Planned

- WFEIS demo to the USFS Rock Mountain Research Station in late summer or fall
- Manuscript to be submitted to International Journal of Wildland Fire describing the WFEIS with demonstrations of outputs
- Manuscript comparing WFEIS to CanFIRE to assess model similarities and differences.

8. Recommended Next Steps

Extension of WFEIS for on-going projects

The current version of WFEIS is considered a prototype. The intention is to provide access to data sets and results of emissions to provide real estimates for some situations and to demonstrate the capabilities of the system for further development. In addition to the possible extensions of the system and improved data inputs reviewed here, a required improvement for future versions should include estimates of output uncertainties. The data to create an uncertainty evaluation exists, but in forms difficult to use, in some cases. Also, development of a method to compute and describe the uncertainly needs to happen. We see this as a priority for the scientific applications for which the system is valuable.

The system as completed for the project operates in forested and some shrubland types, and is not operational for some rangeland areas and all croplands. In an on-going NASA-funded Applied Science Program project (#NNX09AP53G lead by A. Soja) the WFEIS team is currently developing WFEIS to operate for agricultural regions of CONUS. In an additional NASA sponsored project under the Terrestrial Ecology Program (#NNX10AF41G), PI French is funded to look at emissions from the tundra regions of North America. Both of these projects were awarded after the WFEIS development was underway with the idea that the system could be augmented to work in these additional settings.

Also part of the Agriculture and Rangeland burning project (#NNX09AP53G) we are developing additional WFEIS query capability. The project end user is the EPA CMAQ development team. The idea is to provide access to emissions model outputs for this team that coordinates with their needs. Some of these are to tag the emissions by EPA Source Classification Code (SCC) and provide outputs for EPA criteria pollutants. Another is to integrate additional emission factors for non-forested sources. As these corollary projects proceed, the WFEIS system will be maintained and augmented to some degree to address the project needs.

Improved spatial data sets

Burn area data sets

Burn area mapping is constantly being imporved and new products developed. For future versions of WFEIS, additional and updated bunr area producys should be integrated with the system. In particular, the MODIS burn area product will soon be available, and could be brought into WFEIS as one of the analysis choices.

For some specific studies, we developed some fire progression maps to be used within the WFEIS. These maps were helpful for proper definition of the fuel conditions (moisture) because we could better approximate the area burned on a particular day and apply the weather-based moistures. Future improvements in WFEIS could include mapping fire progression using the Landsat-derived MTBS perimeter with MODIS-designated fire timing. This progression mapping is done at the University of Maryland by project collaborators and is modified from work described in *Loboda and Csiszar* (2007).

Fuels mapping

The fuels maps for CONUS is updated and improved by inclusion of 78 new fuelbeds and crosswalk to a more recent and detailed vegetation layer (EVT). A fuels map for Alaska based on FCCS now exists for the first time. Because these maps are classifications, they fit within the existing structure of WFEIS via simple lookup tables, through which estimates of available biomass (and carbon) for consumption can be made. Fuels are highly variable at multiple spatial scales, however (*Keane et al.* 2001); in reality each 1-km cell will have a unique set of fuel loadings different from the default values for its class. We envision the following improvement to the fuels map, enabled by ongoing improvements to WFEIS. Using MODIS products (particularly Leaf-Area Index and Vegetation Continuous Fields), we can match each cell in the FCCS map layer to specific fuel loadings in satellite-visible upper vegetation layers – e.g., tree canopy for forests, shrub canopy for shrublands, grass coverage for grasslands. This process will produce a more complex data structure than we currently have (now it is classification plus lookup table), and will require a new more complex interface to WFEIS, but will improve the accuracy of continental-scale fuels estimates and better represent their variability.

The current map of standard FCCS fuelbeds included areas of zero fuel loading in non-forested croplands. One task under the NASA Applied Science project mentioned above is to update the FCCS 1-km map to include croplands. Cropland fuelbeds are very simple. With the exception of sugarcane, which includes an organic soil layer that can burn, cropland sites include only a litter stratum. Measurements of fuel loadings and consumption completeness are available from the literature (and one of the study partners) and are being integrated with WFEIS under this other project. Because cropland fuels can change each year and vary by season (in some cases two crops are planted in one year) WFEIS will be enhanced to operate with varying fuel loads by season and year.

With the addition of MODIS products for forests and cropland data for agricultural sites, we envision a seasonally and annually dynamic fuel loading across the CONUS (and possibly Alaska) in a future version of WFEIS using information described above. The development gains made in the US can be ported to Mexico and Canada as well to make improvements in fuels mapping across North America.

Fuel moisture mapping

Currently, daily maps of NFDRS 1000-hr fuel moisture values are generated by the National Interagency Fire Center (NIFC)[34]. These maps are produced by identifying the 12 fire weather stations nearest to each grid cell, and then weighting each of the 12 stations by an inverse distance squared algorithm (L. Bradshaw, USDA Forest Service, pers. comm., 2005). The maps are created operationally using the stations that have reported in at the time of generation. Images of these maps are archived, but not the station data nor the interpolated data products.

[34] http://www.wfas.net/index.php/fire-danger-rating-fire-potential--danger-32

Future efforts may involve mapping the adjusted 1000-hr fuel moisture instead of the standard equations (*Ottmar and Sandberg* 1985). The adjusted 1000-hr fuel moisture equations have been shown to work better in the Pacific Northwest, but have not been fully tested elsewhere. An effort to improve the equations could include regionally-calibrated equations. In addition we would investigate different interpolation schemes, weather data sources and smaller ecoregion aggregation. Also possible could be a daily dynamic mapping rather than aggregating to ecoregions.

Duff moisture maps could be improved with many steps. First, the conversion of weather-derived DMC to percent moisture is not well-developed nor tested. A rigorous review of the conversion and assessment of the appropriateness of the FWI DMC for this should be done. Once improvements are made, a full validation of the weather-based algorithm should be performed.

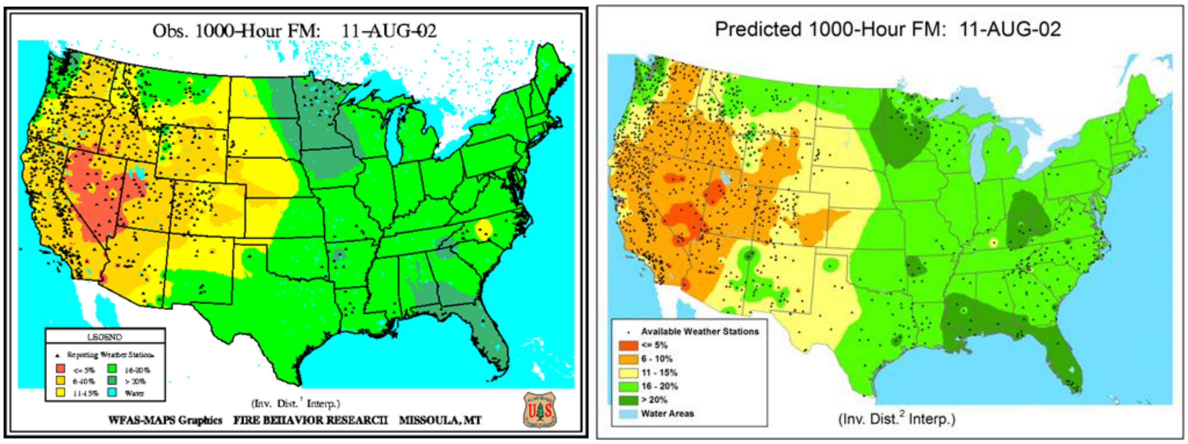

Figure 5: Left: Archived NFDR 1000-hr fuel moistures from the US Forest Service Wildland Fire Assessment System (http://www.wfas.net/index.php/dead-fuel-moisture-moisture--drought-38). Right: NFDRS 1000-hr fuel moistures recalculated for the WFEIS database. The recalculated maps will be the basis for proposed improvements to spatial fuel moisture mapping.

Canopy consumption and shrub blackened inputs to python-consume

Two inputs to python-consume were devised as user inputs in the original use of CONSUME 3.0, so for WFEIS we needed to define methods to populate these inputs in a logical manner for any WFEIS run. The algorithm used within WFEIS to decide on the percent of canopy consumed is based on the crown fire potential of the fuelbed. This algorithm has not been checked. The assumptions of crown fire potentials as indicators of consumption, the cut-off value chosen, and the application of the equation were developed from expert advice. The algorithm should be tested and modified or replaced with more rigorous study. Similarly, a decision was made to have the shrub blackened input set to 50%. This is not ideal; current research on shrub consumption in forests and rangeland fuel types needs to be integrated into the WFEIS method of populating this input parameter.

Conversion of biomass to carbon

Currently, the WFEIS estimates of total carbon emission are computed as one-half of the fuel consumption, which does not account for the variability in carbon content of the various fuel components (strata). This is because the CONSUME model does not include a specific output of total carbon. Emissions of specific components are derived by summing up the emission-factor-derived emissions from each stratum (emission factors are computed from the amount of dry fuel consumed in each stratum). Estimates of total carbon emissions can be made in a more sophisticated manner by deriving total emissions by fuelbed and strata to account for the lower density of carbon in the duff layers and varying content in other plant tissues and types.

Information system improvements

Use of dynamic fuels: WFEIS currently models with fuels being static in time, while in reality the fuels are changing due to disturbance and seasonal changes. WFEIS could be enhanced by modeling the fuelbeds as (stepwise) variable in time with the system choosing the fuels based on the date range of the query.

User-designated regions of interest: WFEIS currently allows for bounding box queries (aligned with latitude and longitude) and for predefined regions-of-interest (ROIs) such as states or ecoregions. In the future, this could be expanded to allow for user-generated ROIs so that users have greater control and flexibility of the spatial extent over which emissions are estimated.

WFEIS calculator upgrades:

- Include addition regions of interest (e.g. US National Forests/National Parks/Wildlife refuges, etc)
- Allow for grid resolution in m/km in addition to degrees of lat/long
- Development of GUI functionality to allow users to generate and submit custom ROIs.

Web site improvements:

- Need full review & editing with more rigorous user feedback of site information and calculator functionality.
- Add more documentation that describes all of the options that are available via the RESTful interface. Provide examples of writing scripts in programming languages that use the REST API to download discrete time series of emissions estimates.

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