Project Title: Predicting Prescribed and Wildland Fire Smoke, Emissions, and Fire Characteristics in Deep Organic Soils

Final Report: JFSP Project Number: 08-1-3-03

Principle Investigators:

Robert Mickler, Alion Science and Technology, 100 Park Forty Plaza, Suite 200, Durham, NC 27713; Phone 919.406.2104; E-mail: rmickler@alionscience.com

Miriam Rorig, USDA Forest Service, PNW Research Station, 400 N 34th, Suite 201, Seattle, WA 98103; Phone: 206-732-7843; E-mail: mrorig@fs.fed.us

Christopher Geron, US EPA, National Risk Management Research Laboratory, E305-02, Research Triangle Park, NC 27711; Phone: 919.541.4639; E-mail: Geron.chris@epa.gov

Research Associates:

David Welch, Alion Science and Technology, Durham, NC

Candace Krull, USDA Forest Service, Seattle, WA

Mark Moore, USDA Forest Service, Seattle, WA

Abstract

The management of prescribed and wildland fire on federal, state, and private lands with deep organic soils pose critical challenges for ecosystem management, smoke dispersion, and the protection of private property and human life. Several regions in the US contain significant areas of deep organic soils, the boreal forests of Alaska and the northeastern US, the peat bogs in the glaciated northeast and Great Lakes, and the pocosins in the southeastern and Gulf coasts. We characterized fuel and fire effects in four representative sites with deep organic soils in North Carolina. Study areas include the Alligator River and Pocosin Lakes National Wildlife Refuges, the Croatan National Forest, and The Nature Conservancy's Green Swamp Preserve. The project objectives were to: (1) Determine the relationships between meteorology, soil characteristics, litter/duff moisture, micro-topography, and fire behavior in the ignition, flaming, smoldering, and extinction combustion stages; (2) Characterize smoke concentration and trajectory with the BlueSky modeling framework and the effects of organic soil ground fire on the National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ and ozone; (3) Quantify pre- and post-burn below- and above-ground biomass to determine fuel characteristics and consumption for fine and coarse woody material, shrub, herbs, litter, and duff; (4) Characterize photochemically/radiatively important trace gases during combustion stages of prescribed and wildland fires; (5) Conduct laboratory burn simulations in the EPA's open burn test facility (OBTF) to relate burn duration, burn depth, fuel consumption, heat release, and emissions to organic soil properties and meteorology; (6) Compare and contrast laboratory controlled combustion and wildland/prescribed fire emissions for the same organic soil series; and (7) Provide land manger with decision support tools for managing prescribed and wildland fire and assessing ground fire risk on deep organic soils.

I. Background

1. Project Justification

All prescribed and wildland fires on vegetation with organic soils result in some ignition loss of organic soil. Whether this loss is significant is often dependent on the skill and experience of the prescribed fire manager. Duff moisture, depth to the ground water, recent precipitation, burn history, live fuel moisture, and the weather forecast for the burn day and subsequent days are often used to make go/no go decisions for ignition. A wrong decision often leads to costly ground fire mop-up costs and the loss of several feet of organic soil that accumulated over several hundreds of years. Wildland fires on the deep organic soils in the coastal plain of North Carolina and throughout the southeastern US pose significant risks to wildlife refuges, national forests, and private lands. Wildland fires accelerate the destruction of pocosin ecosystems and conversion of forest types in response to elevation changes from the loss of organic soils. Fire in the organic soils of the coastal plain is often the result of frequent and costly blowup wildfires from lightning ignitions and the use of prescribed fire as a fuel reduction and habitat management tool. Wildfires and prescribed burns in this area can, under certain combinations of fuel and weather, grow from a low intensity burn to a virtually uncontrollable ground fire until weather conditions change or fire crews pump sufficient water on the area. Control efforts are often hampered by inaccessibility, poor soil trafficability on wet organic soils in the area, and fires that tend to burn deeply into the organic soils for several months. A better understanding of the behavior of fires and the role of fuel loading and condition in fire behavior in the pocosins, especially the factors that contribute to the occurrence of major ground fires, will contribute to the control of wildfires and the use of prescribed fire as a management tool in the region.

Landscape level fire risk assessments being developed for US Fish and Wildlife Service refuges and USDA Forest Service's National Forests include the impact of smoke on communities, sensitive receptors, and infrastructure. An essential component of the risk assessment within each airshed is the ability to model concentrations and dispersion of particulate and chemical emissions for fuel models on deep organic soils. Estimating the carbon loss and emissions from deep organic soil fires has substantial uncertainty associated with the estimate because of (1) spatial variation in fire intensity, (2) heterogeneous mixture of organic decomposition and mineral components; and (3) variable depth, bulk density, and proximity to the water table of the Oa horizon in the region's organic soils. Land managers agree that improving our understanding of prescribe and wildland fire behavior on deep organic soils is imperative to the planning and go/no go decision making process. Our study enhances our knowledge of ground fire behavior, quantifying emissions, and predicting smoke production and dispersion during ignition, flaming, smoldering, and extinction stages of fires.

2. Project Objectives

The project objectives are to: (1) Determine the relationships between meteorology, soil characteristics, litter/duff moisture, micro-topography, and fire behavior in the ignition, flaming, smoldering, and extinction combustion stages; (2) Characterize smoke concentration and trajectory with the BlueSky modeling framework and the effects of organic soil ground fire on the National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ and ozone; (3) Quantify pre- and post-burn below- and above-ground biomass to determine fuel characteristics and consumption for fine and coarse woody material, shrub, herbs, litter, and duff; (4) Characterize photochemically/radiatively important trace gases during combustion stages of prescribed and wildland fires; (5) Conduct laboratory burn simulations in the EPA's open burn test facility (OBTF) to relate burn duration, burn depth, fuel consumption, heat release, and emissions to organic soil properties and meteorology; (6) Compare and contrast laboratory controlled combustion and wildland/prescribed fire emissions for the same organic soil series; and (7) Provide land manger with decision support tools for managing prescribed and wildland fire and assessing ground fire risk on deep organic soils.

3. Fire History, Fire Behavior, and Smoke Modeling

Fire has played a major role in determining the distribution of plants across the pocosins of the southeastern US. Throughout the coastal plain of the southeastern United States, land mangers share a similar problem. Fires ignited in deep organic soil by lightning and humans can result in wildfires that put communities in the wildland urban interface at risk. Wildfire behavior on deep organic soils changes from a low intensity burn to a virtually uncontrollable burn until weather conditions change or the fire has run out of fuel. Fire suppression efforts are often hampered by lack of roads, poor trafficability on deep organic soils, and fires that tend to burn deeply into the organic soils during periods when the water table is low.

Inventorying, mapping, and modeling down woody debris and fuels biomass and developing fuel loading formulas has been identified by fire managers as a critical need for improving our current understanding of communities at risk in the wildland/urban interface, and wildland fire use. Continued refinement and validation of the BlueSky smoke dispersion modeling framework will ensure a dependable, accurate smoke model for the continued improvement and refinement of our prescribed burning program and assist in the fire manager's response to wildland fire. Characterizing trace gas and particulate emissions from prescribed burns will enhance dialog between the US EPA and state/county air quality regulatory agencies responsible for compliance with revised National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$, PM_{10}, ozone, and state smoke management guidelines.

Fuel, Climate, and Combustion Stages: Recent studies investigating the factors that influence smoldering in organic soils have demonstrated that moisture and mineral content are the major

factors that influenced sustained smoldering (Reardon et al., 2007; Frandsen, 1997). Reardon reported that the chance of smoldering decreased by 19.3% for each 5% increase in soil moisture and the chance of smoldering increased by 155.9% for each 1% increase in mineral content. The depth of consumption was shown to be dependent on the soil moisture profile and not the height of the water table in the soil profile. Previous work was conducted using cellulose and polyurethane as a surrogate for heterogeneous organic soils (Ohlemiller, 1995). These studies concluded that although the initial ignition was dependent on fuel properties, the nature of fuels was less important than the oxygen flow during the continuing propagation of the smoldering stage of the burn. This work was repeated in several studies using peat moss and the results demonstrated that moisture, mineral content, and radiant energy from flaming combustion are the primary factors that influence sustained smoldering.

The fuel and weather conditions that determine whether fires will ignite, and are associated with transitions between combustion stages, are not easily measured. This is due partly to the highly variable nature of fuels on the landscape, and the lack of a dense network of sensors to monitor weather and fuel conditions. Previous studies have shown success in using Time Domain Reflectometry (TDR) sensors to track fuel moistures in real time. TDR output has been used to predict relative drying trends and combustion limits in pine forests in Florida (Ferguson et al. 2002, Anderson et al. 2003). These results have proven to be very useful for planning prescribed burns under varying soil moisture conditions and facilitating links to the National Fire Danger Rating System (NFDRS). Presently, fire managers in the southeastern US rely on the Keetch-Byran Drought Index (KBDI) to provide a cumulative measure of soil moisture and weather parameters to assess the risk of ground fire. The KDBI and the professional opinion of the burn boss, a result of years of experience in conducting prescribed burns and responding to wildland fires, is often the foundation of a go/no go decision. Additional decision support tools are needed for fire managers that are easy to use and can be integrated into Prescribed Burn Plans and the Complexity Rating Worksheet.

Fire Characteristics, Fuel Consumption, and Smoke: Fuel classification has evolved from a fire control planning focus to the beginning of predictive fire behavior modeling in the 1970s. Current fuel classification models have focused on the rate of spread, resistance to control, and the flame length of fires in surface fuels. Fire behavior is predicted by land managers with thirteen stylized fuel models (Rothermel, 1972; Albini, 1976). Decision support systems such as FARSITE and the National Fire Danger Rating system are based on the Rothermel's fire spread model and are the basis of predicting fire behavior today. Land managers recognize that these models are limited in their ability to predict extreme fire behavior, persistent fires, and fuel consumption. Some of the fuel information limitations are currently being addressed by the Fuel Characteristic Classification System (FCCS) research funded by the JFSP. But of the original 13 and new 40 standard fire behavior fuel models, few adequately characterize fuels found in pocosin forest types in North Carolina and Virginia.

The availability of fire-spread models has increased the need for quantitative fuel field data. A line-intersect method developed by Brown (1974) has been widely adopted and is being used by the USDA Forest Service Forest Inventory and Analysis (FIA) program to quantify fuel-loading inputs. The FIA methods generally partition the forest ecosystem into pools for live trees, down deadwood, standing dead trees, understory vegetation, forest floor materials, and soil. The contribution of deep organic soils to fire fuel and carbon assessments has not been addressed to date. Past fuel and fire behavior research has resulted in only qualitative measures of fuel loads and rates of spread.

***Burning Emissions Monitoring and Modeling*:** Landscape scale emissions of trace gases and PM are typically determined using the approach of Taylor and Zimmerman (1991) and Hao and Liu (1994):

$$M = A \bullet B \bullet \alpha \bullet \beta$$

where *M* is the amount of biomass consumed annually, A is the total land area burned annually (ha yr^{-1}), B is the average organic matter (fuel load) per unit area in individual biomes (metric tons or MT ha^{-1}), α is fraction of above ground biomass to total, and β is the burning efficiency (fraction consumed) of the above ground biomass. Total emission of a given compound is given by multiplying *M* by an emission factor, which is typically expressed in units of g-C/kg-C fuel consumed.

These emission factors (EF), and total emissions of trace gases and PM from individual fires are typically determined using a carbon mass balance approach as described in Ward et al. (1988) as:

$$F_t = \left[\frac{C_t}{(C_{CO2} + C_{CO} + C_{CH4} + C_{TPM} + C_{VOC}}\right] CS_F$$

where F_t is the flux of the target compound(s), C_t is the concentration of the target compound(s), $C_{CO2,CO,CH4,TPM,VOC}$ are sample concentrations of CO_2, CO, CH_4, total PM, and total VOC, respectively, and CS_F is the fuel consumption (carbon mass) per unit area. Nitrogenous emissions are calculated similarly. We have recently used these approaches in our JFSP project to calculate EFs and total emission fluxes from the coastal plain prescribed fires in North Carolina. The mass balance approach takes advantage of the turbulent state of mixing in fire plumes, which means that particles and gases will be transported in similar proportions as they move from the source. This allows us to make valid mass balance estimates of PM and gases in plumes that cool to ambient conditions, appropriate for assessing impacts on air quality and atmospheric chemistry.

Continuous monitoring of ozone (O_3), PM, and oxides of nitrogen (NO_x) have shown that air pollutant concentrations are enhanced by forest fire emissions. In the rural environment, the influence of the forest fire on air quality can be detected, and significantly higher (50-150%) pollution levels than seasonal median values have been documented (Cheng et al., 1998). While fire events can cause high transient air pollutant concentrations, the fire emissions are a relatively small fraction of the annual emission inventory. For fine particulate matter, however, the annual emission estimates from biomass burning represent a significant fraction of many states' emission inventories (Dennis et al., 2002). Given the current emphasis by the EPA on particulates, it is imperative that real-world emission data from open burning sources be developed.

It is generally thought that emission factors (EF) or pollutants are among the more consistent and reliable components of biomass burning emission models. However, comparisons of recent studies suggest that under some conditions emission factors (EF) are still quite uncertain (Andreae and Merlet, 2001; Hays et al., 2002). Residual smoldering combustion (RSC) emissions from forest floor burns can be produced for up to several weeks after the passage of a flame front and they are mostly unaffected by flames. Fuels prone to RSC include downed logs, duff, and organic soils. These fuels are very important in our study areas.

Smoke Modeling: Smoke emissions from wildland fires are one the most important constraints on land mangers conducting prescribed burns. The quantity, duration, time of day, and spatial dispersion of smoke must all be considered when assessing impacts on human health and safety. Existing smoke models do a poor job of estimating smoke production and duration. This is especially true on the deep organic soils found in North Carolina. Many of the dispersion models in use by wildland mangers today (SASEM (Sestak and Riebau, 1988), VALBOX (Sestak et al., 1989), VSMOKE (Lavdas, 1994), NFSpuff (Harison, 1995), TSARS (Hummel and Rafsnider, 1995), and CALPUFF (Scire et al., 1994)) have been adapted from industrial stack

models for use in wildland fires. The FARSITE (Finney, 1998) model was developed to address these data requirements and is used to model forest fire behavior in variable fuels, terrain, and changing local weather conditions.

The BlueSky smoke modeling framework (http://blueskyrains.org), developed with support from the JFSP, is a smoke prediction tool used by land managers to facilitate wildfire containment and prescribed burning programs, which are necessary for ecosystem health, while minimizing impacts to human health and scenic vistas. The BlueSky smoke modeling framework links computer models of weather prediction, fuel consumption and emissions by fire, and smoke dispersion into a system for predicting the cumulative impacts of smoke from prescribed fires, wildfires, and agricultural fires (O'Neill et al. 2005, O'Neill et al. 2003). BlueSky is currently functional over the conterminous United States. Since BlueSky was first made available, work has continued to improve, test, and validate the modeling framework. JFSP project 03-1-3-09 was funded to implement an automated system for evaluating BlueSky predictions. We recently completed working on one project to validate BlueSky in the coastal plain of the southeastern U.S. (JFSP project 04-2-1-80), and on another to calibrate, or "tune" the model by measuring smoke from wildfires to compare observations with predictions (JFPS project 06-1-1-12). These projects have given us the opportunity to compare predictions to observations in real-time, and also to go back and re-run BlueSky after the fact, to determine which inputs are most sensitive to predictions of PM2.5. Preliminary results indicate that accurately characterizing fuel types and fuel loadings, accurately locating the actively burning front of wildfires, and inputting realistic values for the duration of prescribed burns all have a large impact on the predicted location and concentration of smoke.

II. Study Description and Location

1. Study Sites

Work was performed on federal properties in North Carolina where fire management on organic peat soils provides significant management challenges. The Alligator River and Pocosin Lakes National Wildlife Refuges and US Department of Defense Air Force Dare County Bombing Range are located on the coastal plain in eastern North Carolina where peat soils make up nearly 90% of the land area. The diverse habitat types include high and low pocosin, bogs, fresh and brackish water marshes, hardwood swamps, and Atlantic white cedar swamps. All North Carolina study sites have suffered from widespread wildfires in the past, and managers are attempting to mitigate future wildfires through the use of prescribed fire programs. The Nature Conservancy Green Swamp Preserve contains some of the country's finest examples of longleaf pine savannas. The open savannas have a diverse herb layer with many orchids and insectivorous plants. Almost 13,000 acres of the preserve, however, are comprised of a dense evergreen shrub bog (pocosin) dominated by gallberry, titi, and sweetbay. Five major forest types and three non-forested types of plant communities comprise the swamp vegetation. The forested types include pine, Atlantic white-cedar, maple-blackgum, tupelo-baldcypress, and sweetgum-oak poplar. The non-forested types include a remnant marsh, a sphagnum bog, and an evergreen shrub community. Currently red maple is the most abundant and widely distributed plant community, as it expands into other communities due to the lingering effects of past forest cutting, extensive draining, and the exclusion of forest fires. Tupelo-baldcypress and Atlantic white-cedar are found in long fire interval landscapes. We monitored prescribed and wildland fires in North Carolina during the study. Most wildfires occur in North Carolina during the spring and prescribed fires are normally conducted as dormant season burns from October through March. Sampling design for field and laboratory studies are discussed in each Methods section.

3. Methods

Duff Moisture and Meteorology*:* In order to monitor the moisture content of the organic layers,

we installed portable weather stations equipped with the TDR sensors. The electromagnetic sensors afford an economical means of monitoring fuel moisture remotely and continuously, and provide a dynamic representation of moisture fluxes throughout the season, over winter, and through the freeze and thaw cycles. The disadvantage of using the TDRs is that they are not easily calibrated, and therefore they provide a relative, rather than absolute, measure of fuel moisture. The primary advantage to using TDRs is that they continuously measure fuel moistures, and data collection can be automated. The alternative is to use destructive sampling techniques, which are time-consuming and realistically cannot be conducted more than once every several days, especially in remote areas.

We installed weather stations that will measure air temperature, relative humidity, wind speed and direction, and duff moisture from the TDR sensors. In addition, the stations include fuel stick moisture and fuel stick temperature sensors, and at least one will have barometric pressure and precipitation sensors. These stations were equipped with communication equipment, and the data was downloaded and processed for display on the web site. The downloaded data was made immediately available on our web site for land managers to access and use.

***Smoke Dispersion**:* The AirFIRE team, led by Co-PI Miriam Rorig provided a forecast of expected weather and smoke behavior before each experiment, gathered on-site meteorological information, and ran and tested the BlueSky smoke prediction system (www.fs.fed.us/bluesky). The forecast is necessary to help anticipate fire and smoke behavior and to determine the most effective observational configuration. On-site meteorological information was used to validate and improve the weather components of BlueSky. A standard configuration of BlueSky was run to help with pre-burn forecasting and be used to demonstrate the uncertainty in predicting smoke in the region. An enhanced configuration of BlueSky was run with measured information from each experiment to help quantify areas of needed improvement.

Before each experiment we ran a standard configuration of the BlueSky smoke modeling system (www.fs.fed.us/bluesky), which used the CALPUFF dispersion model. The system was rerun following each experiment in an enhanced mode that adjusts available pre-burn information with information that was measured during the experiment. The two runs were compared to quantify uncertainty in the modeling system and determine areas of needed improvement.

The monitoring of particulate matter (PM) in ground level smoke plumes from prescribed and wildland fires was conducted using continuous PM monitors, the MetOne, Inc. EBAM (Environmental Beta Attenuation Monitor). The Met One E-BAM is a portable real-time beta gauge traceable to US-EPA requirements for automated $PM_{2.5}$ measurement. Accuracy and precision of the $PM_{2.5}$ data is consistent with US-EPA requirements for Class III designation for $PM_{2.5}$. The E-BAMs was fitted with $PM_{2.5}$ inlets. Meteorology sensors collected wind speed and direction, air temperature, relative humidity, and barometric pressure. The data from the E-BAM units was recorded by digital data loggers using the analog signal outputs of the monitors. The data from the E-BAM monitors and meteorology sensors will be recorded as 5-minute, hourly, and daily (midnight-to-midnight) averages. The proposed E-BAM monitoring network was comprised of stations in simultaneous operation during prescribed fires from prior to ignition to extinction stages of the burn. Wildland fires were monitored at downwind locations based on availability of road access and the safety of the equipment and staff.

***Measurement and Modeling of Down Woody Debris and Fuels**:* We established a permanent plot network on the prescribed burn sites on study sites in North Carolina. The biomass plots were modeled on protocols developed for the USDA Forest Service FIA and Fuel Characteristic Classification System (FCCS). We measured and characterized live biomass and pre- and post-burn down deadwood (DWD) on a minimum of two prescribed and one wildfire site in each of the two years of the study. The collection of DWD data used a line-intersect method to sample

down wood along linear transects. Down deadwood was characterized as coarse woody debris (woody pieces greater than 3.0 inches in diameter), or fine woody debris (small = 0 to 0.24 inch, medium = 0.25 inch to 0.9 inch, and large= 1 inch to 2.9 inches, which correspond to 1-hour, 10-hour, and 100-hour fuels, respectively). The depth of the duff layer, litter layer, and overall fuelbed was taken on each plot. These components were used to estimate fire behavior, fire spread, fire effects, and smoke production. Plot-level per-unit-area sums were expanded by the area associated with the inventory plot or averaged across the plots to produce a mean per-unit-area biomass value. Fuel class biomass algorithms were developed for additional forest species and decay classes in the forest types for each burn site. Additional micro plots were established for destructive sampling of shrub and herbaceous vegetation to develop biomass equations.

Field Fire Emissions:

Gas phase emission measurements were performed with instruments acquired with JFSP funds. This includes a Perkin-Elmer GC/MS system with an innovative column splitter which allows a single sample to be analyzed by both Flame ionization Detection for quantitation and Mass Spectroscopy for identification. A portable Photovac FID system (for CH_4 and total non-methane hydrocarbons) was also integrated into the EPA mobile sampling packages. Analytical improvements on both systems continue to be made and will be implemented in the field in additional upcoming studies.

During field sampling, inlets were located on the perimeter downwind of the burn tracts far enough from combustion zones (10-100s of meters) to allow smoke plumes to cool to approximately ambient temperature. This allows partitioning of semivolatiles between gas and aerosol phase. Grab samples during predominantly flaming and mixed flaming/smoldering phases were collected in Summa stainless steel canisters for trace gas analysis using EPA Methods TO-15 and 3C. Target compounds in the gas and PM phase include saturated (alkane) and unsaturated hydrocarbons, aldehydes, ketones, organic acids, and polycyclic organic hydrocarbons (PAH). Continuous total hydrocarbon measurements were also made using EPA Method 25A and a TECO Model 51 THC Analyzer which employs flame ionization detection with no chromatographic separation. This is supplemented by the newly acquired portable FID on EPA's portable package. Dinitrophenylhydrazine (DNPH) cartridges were used to quantify carbonyl emissions (EPA method TO-11A). CO_2 was analyzed via infrared gas techniques (California Analytical Model ZRH CO_2 Analyzer) to account for CO_2 carbon in the mass balance flux techniques and to characterize the nature of plume dispersion and proximity to the combustion zone. We used the CO/CO_2/VOC measurements to help us in chemically identifying the flaming and smoldering stages of the fires in addition to visual assessment.

CO was monitored continuously with EPA Method 10 using gas filter correlation and infrared detection. A Thermo Electron Model 48C Gas Filter Correlation Ambient CO analyzer (Thermo Environmental Instruments, Inc., Franklin, MA) was used.

SO_2 measurements were performed with EPA Method 6C (pulsed chemical fluorescence) using a Thermo Environmental Instruments, Inc, Model 43S (Franklin, MA). NO_X measurements were performed with EPA Method 7E (chemiluminescence) using a Thermo Environmental Instruments, Inc, Model 42S (Franklin, MA).

PM_{10} and $PM_{2.5}$ measurements were made using inertial impaction gravimetric filter techniques (EPA Method IP-10A) upstream from the canisters. These samples were then subjected to particle and total gaseous carbon analysis using a thermogravimetric analysis and gas chromatography/mass spectroscopy (GC/MS). The impactors were backed by polyurethane foam traps for collection of gas phase semi-volatile organic compounds that pass through or are volatilized from the filters (EPA Method TO-10A, see complete sampling and analytical protocol

in Hays et al. 2002). Total emissions are then determined by multiplying by the estimate of total fuel carbon consumption. Total fuel carbon by mass typically ranges from 45-54% of the fuel dry weight, and is assumed to be 50% for this study.

The portable sampling system (developed by Chris Geron for this project) uses twin mini-cyclones (with personal carbonate plastic filter holders) as the inlets, which support 37 mm quarts or Teflon filters for $PM_{2.5}$ sampling. A 3SLPM Licor pump pulls air through one of the cyclone/filter inlets and pushes through a flow restrictor (0.8 SLPM) and then through a Licor 840 CO_2/H_20 infrared gas analyzer. A BRC Rasmussen 5 SLPM diaphragm pump pulls through the second cyclone/filter, then pushes through a "T". On one side of the "T" the Photovac portable FID system, which has its own internal pump, samples at 1 SLPM. The FID was used in both total VOC mode, and also in a CH_4 only mode by using an activated charcoal filter immediately downstream of the unit. When the FID was not deployed, TENAX cartridges were used to sample the particle filled air at 250 Ml min^{-1} using a SKC Pocket Pump. On the other side of the "T", air is pushed through a restrictor to a H_2SO_4 reaction cell for CO detection (flow rate dependent, calibrated at 45 SmLPM).

Filter media used in the impactors and cyclones was 37 mm quartz fiber (for analysis of organic $PM_{2.5}$ components) and teflon (for total gravimetric mass, inorganic ions and elements). Pumps and flow control devices used for sampling were calibrated with a DryCal Flowmeter gas analyzer, a primary calibration standard. All filters were conditioned for 24 hours at 25□C and relative humidity of 38% prior to tare weight determination. Following sample collection filters were again conditioned for 24 hours at 25□C and relative humidity of 38% prior to final weight determination. PM concentration was calculated by subtracting the tare weight from the final weight and dividing by air sample volume. The $PM_{2.5}$ samples were subsequently analyzed in this study using the extraction/derivitization methods discussed in Hays et al. (2002). Levoglucosan was quantified using two dimensional GC technique described in Ma et al (2007).

Background measurements of PM and trace gases were performed by air monitoring prior to fire ignition or performing measurements upwind of active fires. Background values were subtracted from fire samples prior to EF calculations. NIST traceable certified span gases (Scott Specialty Gases, Inc., Plumsteadville, PA) were used to perform five point calibrations of the continuous emission monitors on site prior to monitoring. Serial dilution was performed using a dynamic dilution system (Model 146, Thermo Environmental Instruments, Inc., Franklin, MA).

Laboratory Fire Emissions: Field testing was coupled with controlled laboratory burn studies and analytical experiments. Laboratory burn simulations were conducted in the EPA's open burn test facility in Research Triangle Park, NC which has been used for multiple biomass types (wheat stubble, forest, sugarcane). This facility allows for simulation of open burning under controlled conditions (fuel moisture, air temperature, humidity, and ventilation rate) and allows for emission monitoring and emission factor determination. The goal of these tests is to relate burn duration, burn depth, fuel consumption, heat release, and emissions to the various stages of combustion.

Organic soil samples were gathered via an established sampling protocol that retains physical integrity. Field samples were analyzed for the following properties: moisture profile (depth), density profile (depth), permeability, ignition temperature, and organics composition. Thermogravimetric analyses coupled to gas chromatography/mass spectrometry and differential scanning calorimetry analyses will be conducted on small field samples to evaluate moisture, volatile matter, species evolution with temperature, and sample energetics.

Combustion testing on the OBTF will examine the effects of inlet air temperature (ambient, ~20 ^oC to 38 ^oC), air humidity, ventilation rate (air velocity) and sample size (bed

depth) with each parameter varied over a range of realistic conditions. These controlled parameters will be statistically analyzed with multivariate models to determine their relevance in predicting transitions between combustion stages. The relative ability of each parameter to explain the combustion transition in contrast to other parameters will be determined via squared semipartial correlations (as in Gullett et al., 2000). Results will be compared with published data (Frandsen, 1997). Soil variables (bulk density, moisture, percent organic matter, thickness of Oa horizon, and degree of decomposition) will also be examined to quantify effects on emissions and burn rate and compared to results of others (Reardon et al., 2007). Emissions were sampled in real time, including CO, CO_2, NO_x, Hg, PM, PAHs and HCs via CEMS. These real time measurements allowed for emissions characterization during the varying fuel stages and were coupled with video recordings to examine and record combustion stage transitions. The fuel samples also contained a thermocouple array to further gauge the burn characteristics and transitions between stages.

Continuous emission monitors (CEMs) for carbon monoxide (CO), carbon dioxide (CO2), oxygen (O2), and total hydrocarbons (THCs) received emissions from the transfer duct a via heated (120 ºC) Teflon tubing with an in-line heated (120 ºC) quartz filter. The gases were dried with a refrigerated air drier and silica desiccant prior to measurement. The CEMs were calibrated using compressed gases before and after sampling, including range midpoints, as per procedures in 40 CFR 60 Appendix A, Method 6c. Potential bias due to losses in the sample transfer line was monitored by injecting the calibration gases both at the point of sampling and at the inlet of the gas analyzers. In order to most effectively characterize emissions during different phases of testing, jet REMPI-TOFMS were used as a real time (~1 s) monitor of aromatic organic target analytes, including the 17- PAHs, in the burn facility testing. Jet REMPI-TOFMS consists of the laser induced photo ionization via a resonant two photon ionization method followed by mass selective detection using a time of flight mass spectrometer. It combines high sensitivity (high ppt / low ppb detection limits) with high selectivity (isomer separation). The real time detection creates the ability to follow emissions during flaming and smoldering phases, hereby identifying periods of high emissions of e.g. PAHs. REMPI results can be used to provide feedback on how to sample during field sampling by identifying the prominent periods where emissions of PAHs occur during an open field burning and to understand whether altering burn or composition parameters affect emissions. Background blank tests (sampling without biomass burning) were conducted to ensure that the sampling and analysis methods, potential facility contamination, and ambient feed air concentrations of the target analytes were not causing bias in the tests.

IV. Key Findings

Prescribed Fire Emission Factors

Our measurements of fuel consumption from the prescribed burns generally fall within the range of values assumed in current models and smoke management guidelines (NCDFR, 2006). In cases where fine fuels (such as marsh grass or pine litter) accumulate, fuel loads range from 3-6 tons $acre^{-1}$ (6.8-13.5 tonnes ha^{-1}). Where flammable shrubs (such as gallberry and fetterbush) colonize sites, fuel loads and consumption are be considerably higher. These circumstances occur when fire frequency is reduced and fuels are allowed to accumulate, creating wildfire risks.

			Emission Factors in g/kg (fuel dry weight) % of $PM_{2.5}$											
Location	**Stage**	**Time**	**PM_{10}**	**$PM_{10}M$**	**$PM_{2.5}$**	**$PM_{2.5}Q$**	**$PM_{2.5}M$**	**CO**	**CO_2**	**CO_2c**	**NO_x**	**THC**	**SO_2**	**LG**
Stumpy Pt.	Fl	11:08-12:25	1.42	1.17	NA	0.86	0.63	15.6	1680	1740	0.71	45.7	1.06	6.3 (0.6)
PLNWR	Fl/Sm	14:15-14:47	8.13	11.0	NA	6.12	4.40	168	1530	1560	0.00	8.8	0.23	8.3 (1.3)
Croatan NF	Fl/Sm	14:40-15:10	5.48	5.39	5.40	4.14	3.72	168	1530	1680	6.69	12.7	1.57	2.7 (1.1)
Croatan NF	Fl	15:15-16:00	1.13	0.94	0.67	0.61	0.64	32.1	1770	1690	1.08	4.3	0.29	NA
Croatan NF	Fl	16:00-16:40	0.61	0.48	0.47	0.32	0.38	22.3	1790	1660	0.56	3.3	0.22	NA
Croatan NF	Sm	16:55-18:20	1.43	0.80	1.12	0.99	0.62	34.7	1770	1610	0.79	6.0	0.24	2.6 (1.1)
ARNWR	Fl	11:41-13:02	6.49	2.92	6.49	4.87	2.22	44.2	1730	1700	2.07	10.1	0.55	4.6 (0.4)
ANRWR	Sm	13:47-16:30	3.38	1.67	2.07	2.41	0.84	34.1	950	920	0.81	303	0.43	1.5 (0.2)
Croatan NF	Fl/Sm	11:40-13:03	1.80	NA	1.67	1.63	NA	20.6	1660	1350	0.87	50.1	0.19	7.4 (0.9)
Green Swamp	Fl	12:05-13:35	NA	NA	8.02	8.67	NA	40.1	1750	NA	NA	20	NA	3.1 (0.4)
PLNWR	Fl	10:48-11:44	NA	NA	9.49	10.44	NA	61.0	1710	NA	NA	17	NA	4.5 (0.4)

Stage: Fl=flaming stage, Sm=smoldering stage
PM_{10} determined gravimetrically from Teflon filter in single stage impactor.
$PM_{10}M$ determined from Met One detector, measures PM 0.5 to 10 µm.
$PM_{2.5}$ determined gravimetrically from Teflon filter in single stage impactor.
$PM_{2.5}Q$ determined gravimetrically from Quartz filter in single stage impactor.
$PM_{2.5}M$ determined from Met One Aerocet detector, measures PM 0.5 to 2.5 µm.
CO determined using a Thermo Electron Model 48C Gas Filter Correlation Ambient CO analyzer.
CO_2 determined using GC/TCD analysis on Summa can samples.
CO_2c determined using California Analytical Model ZRH continuous CO_2 Analyzer.
NO_X determined using TECO 42S continuous emission monitor.
THC determined using TECO Model 51 THC continuous total hydrocarbon analyzer.
SO_2 determined using Thermo Environmental Instruments, Inc, Model 43S continuous emission monitor.
LG: Levoglucosan

The emission factors determined from the samples collected during each of the individual prescribed burns (current and previous project) is presented above. CO_2 emission factors are important since they represent the largest carbon component of emissions. For all of the prescribed fires, emission factors for CO_2 are in the upper half of reported ranges (Andreae and Merlet, 2002). This indicates clean, efficient combustion relative to other forms of biomass burning. CO EFs are lower than or similar to previously reported Rx and wildfire values.

Previous studies have found that $PM_{2.5}$ typically composes at least 2/3 of total ambient PM, and roughly 80% of PM_{10} from biomass combustion sources (Andreae and Merlet, 2002 and references therein). Our data is consistent with these proportions. In general, our $PM_{2.5}$ and PM_{10}

EFs were lower or similar to those published in other open biomass burning studies (Vose et al., 1997). Our recent data from PLNWR and Green Swamp were very similar to the $PM_{2.5}$ EFs for coniferous and mixed fine fuels (9-12 g kg^{-1}) applied in the model of by Weidinmyer et al. (2006) for coniferous, mixed, and shrubland fuel classes. The $PM_{2.5}$ EF of 8.0 g kg^{-1} used by Dennis et al (2002) for litter and fine woody fuels is also similar.

The combination of lower PM EFs and higher CO_2 EFs indicates that the prescribed fires exhibited more efficient combustion than wildfires or slash reduction burns. This is likely due to effectively burning primarily fine fuels under prescription conditions, which minimizes consumption of soil organic layers and smoldering of heavy fuels. Combustion of the latter fuel components often results in higher emission of products of incomplete combustion (McMahon et al.,1980; Bertschi et al, 2003). Organic soil burning $PM_{2.5}$ EFs can exceed 40 g kg^{-1} (McMahon et al, 1980; Chen et al, 2007). The soil burning EFs for $PM_{2.5}$ we observe in this study are in agreement with these values.

Soil organic burning was initiated by wildfires at PLNWR (2008) and ARNWR (2011). These fires were ignited by lightning strikes following dry springtime periods. These fires covered over 100,000 acres and were among the largest recently recorded in the eastern U.S. Small amounts of soil organic consumption was also detected and tested during an Rx fire at the Green Swamp in February of 2009. In 2009, emissions from a Rx fire at PLNWR were studied. This fire burned into organic soils and was extinguished after several days. Fuel was collected from this site to perform laboratory and burn hut tests of emissions from peat and organic soil fuels.

Emission factors and total emissions of trace gases and PM from individual fires are typically determined using a carbon mass balance approach as described in Ward et al. (1988) as:

$$F_t = \left[\frac{C_t}{(C_{CO2} + C_{CO} + C_{CH4} + C_{TPM} + C_{VOC})}\right] CS_F$$

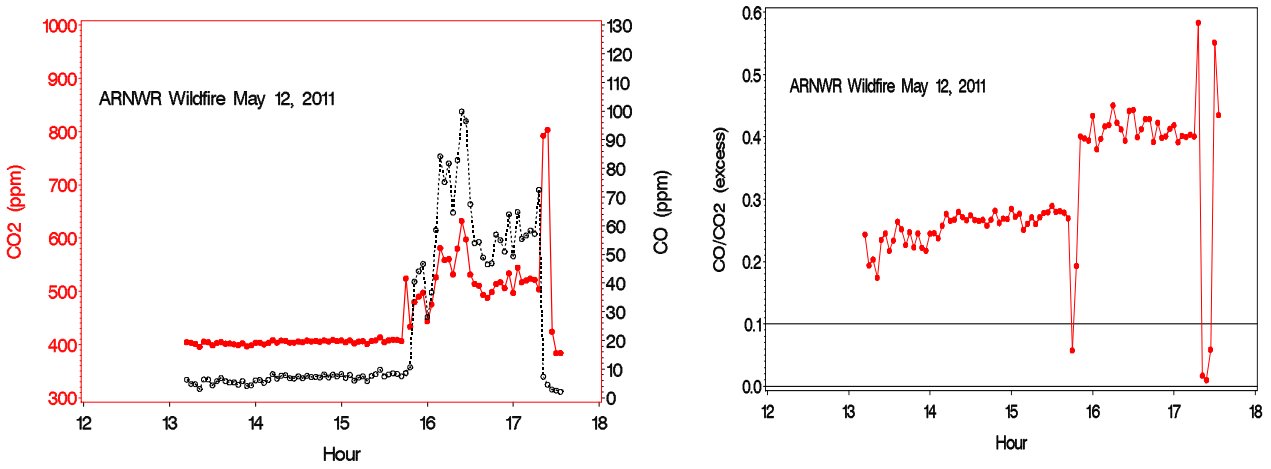
where F_t is the flux of the target compound(s), C_t is the concentration of the target compound(s), $C_{CO2,CO,CH4,TPM,VOC}$ are sample concentrations of CO_2, CO, CH_4, total PM, and total VOC, respectively, and CS_F is the fuel consumption (carbon mass) per unit area. Nitrogenous emissions are calculated similarly. We used these approaches to calculate EFs and total emission fluxes from the North Carolina prescribed and wild fires.

Thus far in the current project, we find that emissions from Rx fires in aboveground fuels are similar to published values. $PM_{2.5}$ EFs from above ground fuels at Green Swamp and Croatan National Forest at 6-10 g/kg. Similarly, Fire in these systems is estimated to emit $PM_{2.5}$ at 8 g/kg values used in the models of Weidinmyer (2006) and others. Similarly, trace gas emission factors are also very similar to those used in current biomass burning emission models. This is also documented in our previous studies on the coastal plain of North Carolina. We recommend that models simulating emissions from above ground fuels should use published values. However, here we find that fires burning into organic soils in North Carolina at Pocosin Lakes National Wildlife Refuge (PLNWR), Alligator River National Wildlife Refuge (ARNWR), and the Green Swamp emit $PM_{2.5}$ and reduced trace gases at rates greatly exceeding model emission factors for these ecosystems. These ecosystems are typically occupied by pond pine (*Pinus serotina*) and loblolly pine (*P. taeda*) pocosins, often with a heavy understory of loblolly-bay (*Gordonia lasianthus* L.), red bay (*Persea borbonia* L.), gallberry holly (*Ilex coriacea* (Pursh) Chapm.),

fetterbush (*Lyonia lucida* Lam. K. Koch) and wax myrtle (*Myrica cerifera* L.).

Pains Bay Fire Emissions on Organic Soils

The figures below illustrate the dramatically different smoke characteristics of soil combustion at the ARNWR wildfire on May 12, 2011. Measurements to hour 15.6 were made in smoke derived from mixed soil/ above ground biomass combustion just east of US Highway 264. Measurements made after 15.6 were dominated by a local soil burning source west of Hwy 264. CO/CO_2 values of 0.2 and 0.4 are much higher than typically observed from burning of above-ground fuels which range from 0.03 to ~ 0.15. This indicates much lower combustion efficiency, which is conducive to high PM and reduced trace gas emissions. $PM_{2.5}$ EFs were also a factor of 4-10 higher than published above ground rates, and ranged from 36 to 65 g kg^{-1}.



Similar observations were recorded from the PLNWR ground fires. In order to isolate the soil source and better understand conditions controlling ignition and $PM_{2.5}$ emission, soil organic matter was harvested from a PLNWR pine plantation where ground fire occurred in 2009. A series of ignitions was attempted as the fuel dried. It did not ignite until moisture declined from over 200% to less than 30%. Ignition was performed using three methods which included a glowing hot plate, butane torch, and lighter ignition with a propellant.

Emission Factors (EFs) from simulated organic soil/peat burning conducted during January, 2010. Fuels are from PLNWR site where Rx fire was conducted during Spring of 2009. EFs are in g kg^{-1} fuel dry weight. Fuels would not sustain ignition above 30% moisture content.

Ignition Method	**CO_2**	**CO**	**$PM_{2.5}$**	**CH4**	**THC**	**CH_2O**
Hot plate	118	298	144	44	172	198
C_4H_{10} Torch	138	217	108	48	187	195
CH_3OH start	73	344	57	50	173	207

Range in EFs from the 3 tests were as follows: CO_2:70-140, CO: 220-340, CH_4: 25-50, THC: 170-190, CH_2O: 195-210, and $PM_{2.5}$: 50-150. These emission factors of PM and reduced gases are at least 10X higher than published above ground fuel EFs. The CO_2 EF is correspondingly much lower. These results highlight the need to separately distinguish ground fires in organic soils when considering fire management practices and air quality. Wildfires with a significant

ground fire component likely have a higher air quality impact than previously thought. Actual (in situ) ground fire emission data is needed.

Emissions of trace gases and particles < 10 and 2.5 microns aerodynamic diameter (PM_{10} and $PM_{2.5}$, respectively) from fires during 2008-2011 on the North Carolina coastal plain were collected and analyzed. Carbon mass balance techniques were used to quantify emission factors (EFs). Emissions from above ground fuels agreed with (or were somewhat lower than) previously published studies as summarized in Andreae and Merlet (2001, and updated in 2008). However $PM_{2.5}$ EFs from extended smoldering combustion of organic soil layers and peat fuels were 2-5X greater than those from grassland and forest burning of above-ground fuels. This is supported by CO_2 EFs at the low end of the previously reported range, indicating less efficient combustion and enhanced emissions of products of incomplete combustion (PICs). CO was also variable relative to CO_2 , with EFs exceeding or at the high end of the range of previously published CO EFs. Total volatile organic compounds (VOC, including CH_4) EFs from peat fuels in laboratory fires were also higher than previously reported EFs for prescribed burning and wildfires in other ecosystems. Organic soil fuel loads and consumption are very difficult to estimate, but are potentially as high as 1000s of tonnes ha^{-1}. This suggests that these higher EFs may contribute substantially to the atmospheric impacts of fires where organic soils may be consumed. The burning of organic soils produced the fire tracer levoglucosan at percentages of $PM_{2.5}$ similar to that from above ground fuels. This suggests that the composition of cellulose in the below ground organic fuels tested is not significantly different from that of the above ground fuels.

Pains Bay Fire Total Hydrocarbons

Total hydrocarbon (THC) data collected using EPA Method 25A employs flame ionization detection with no chromatographic separation, and therefore includes methane. Previous biomass burning EFs for THC range from 4-20 g kg^{-1}. Our Rx EFs fall into the lower half of this range, while soil burning EFs exceed this range.

Pains Bay Fire VOCs and Aldehydes

Acetone is a dominant VOC measured at these fires. Benzene emissions were also significant, followed by other BTEX compounds. Toluene, styrene, xylenes, and ethylbenzene all were found in the gas phase. Formaldehyde emissions from soil organic burning were roughly 10 times higher than AG fuels. This difference was even greater in the burn hut peat tests. Preliminary estimates of organic acids indicate that they account for a higher than expected percentage of gas phase and $PM_{2.5}$ mass. This is probably due to the moist nature of organic soil fuels. Ground fires are often noted to emit a particularly acrid smoke, which is likely to be due to moist, acidic conditions.

	Pains Bay Wildfire (Sm)	ARNWR Rx (Fl)	ARNWR Rx (Sm)	PLNWR Rx (Fl)	PLNWR Rx (Sm)
VOCs **EPA Method TO-15**					
Dichlorodifluoromethane (Freon 12)	NF	0.47 ppbv	0.54 ppbv	NF	NF
1,2 Chloro- 1,1,2,2-Tetrafluoroethane	NF	NF	NF	NF	NF
Chloromethane	17.95 ppbv	2.66 ppbv	NF	NF	NF
Vinyl chloride	NF	NF	NF	NF	NF
1,3-Butadiene	9.32 ppbv	NF	NF	NF	NF
Bromomethane	4.41 ppbv	NF	NF	0.22 ppbv	NF
Chloroethane	NF	NF	NF	NF	NF
Trichloromonofluoromethane	NF	0.29 ppbv	0.28 ppbv	0.3 ppbv	NF
1,1-dichloroethene	NF	NF	NF	NF	NF
1,1,2-trichloro-1,2,2-trifluoroethane	NF	NF	NF	NF	NF
Ethanol	1.08 ppbv	2.35 ppbv	8.53 ppbv	4.26 ppbv	1.21 ppbv
Carbon disulfide	NF	NF	NF	4.06 ppbv	NF
Isopropyl alcohol	NF	1.38 ppbv	0.84 ppbv	1.26 ppbv	0.6 ppbv
Methylene chloride	NF	6.27 ppbv	3.97 ppbv	4.8 ppbv	2.65 ppbv
Acetone	74.56 ppbv	27.67 ppbv	NF	43.87 ppbv	9.22 ppbv
t-1,2-dichloroethene	NF	NF	NF	NF	NF
Hexane	15.02 ppbv	1 ppbv	0.93 ppbv	NF	NF
Methyl-t-butyl ether (MTBE)	NF	NF	NF	NF	NF
1,1-Dichloroethane	NF	NF	NF	NF	NF
Vinyl acetate	2.05 ppbv	0.96ppbv	NF	NF	NF
cis-1,2-dichloroethene	NF	NF	NF	NF	NF
Cyclohexane	2.24 ppbv	NF	NF	NF	NF
Chloroform	NF	NF	NF	NF	NF
Ethyl Acetate	9.05 ppbv	0.61 ppbv	0.58 ppbv	NF	NF
Tetrahydrofuran	NF	NF	NF	NF	NF
1,1,1-trichloroethane	NF	NF	NF	NF	NF
Carbon Tetrachloride	NF	NF	NF	NF	NF
2-Butanone	NF	2.65 ppbv	NF	NF	NF
Heptane	10.86 ppbv	NF	NF	NF	NF

	Pains Bay Wildfire (Sm)	ARNWR Rx (Fl)	ARNWR Rx (Sm)	PLNWR Rx (Fl)	PLNWR Rx (Sm)
Benzene	68.14 ppbv	9.4 ppbv	3.23 ppbv	1.05 ppbv	1.59 ppbv
1,2-dichloroethane	NF	NF	NF	NF	NF
Trichloroethylene	NF	NF	NF	NF	0.66
1,2-dichloropropane	NF	NF	NF	NF	NF
Bromodichloromethane	NF	NF	NF	NF	NF
1,4-dioxane	NF	NF	NF	NF	NF
cis-1,3-dichloropropene	NF	NF	NF	NF	NF
Toluene	28.75	5.54 ppbv	1.98 ppbv	1.74 ppbv	1.59 ppbv
4-methyl-2-pentanone (MIBK)	NF	NF	NF	NF	NF
t-1,3-dichloropropene	NF	NF	NF	NF	NF
Tetrachloroethylene	NF	NF	NF	NF	NF
1,1,2-trichloroethane	NF	NF	NF	NF	NF
Dibromochloromethane	NF	NF	NF	NF	NF
1,2-dibromoethane	NF	NF	NF	NF	NF
2-Hexanone	NF	NF	1.76	NF	NF
Ethylbenzene	7.03 ppbv	NF	NF	0.53 ppbv	0.49 ppbv
Chlorobenzene	NF	NF	NF	NF	0.36 ppbv
m/p-Xylene	9.93 ppbv	2.49 ppbv	0.89 ppbv	1.78 ppbv	1.33 ppbv
o-Xylene	9.38 ppbv	0.76 ppbv	NF	0.59 ppbv	0.55 ppbv
Styrene	3.96 ppbv	0.95 ppbv	0.30	NF	NF
Tribromomethane	NF	NF	NF	NF	NF
1,1,2,2-tetrachloroethane	NF	NF	NF	NF	NF
1-ethyl-4-methylbenzene	NF	0.67 ppbv	0.27 ppbv	NF	0.66 ppbv
1,3,5-trimethylbenzene	NF	0.68 ppbv	0.26 ppbv	0.26 ppbv	Below MDL
1,2,4-trimethylbenzene	2.30 ppbv	1.1 ppbv	NF	1.08 ppbv	0.76 ppbv
1,3-dichlorobenzene	NF	NF	NF	NF	NF
1,4-dichlorobenzene	NF	NF	NF	NF	NF
Benzyl chloride	1.97 ppbv	NF	NF	NF	NF
1,2-dichlorobenzene	NF	NF	NF	NF	NF
1,1,2,3,4,4-hexachloro-1,3-butadiene	NF	NF	NF	NF	NF
1,2,4-trichlorobenzene	NF	NF	NF	NF	NF

Stage: Fl=flaming stage, Sm=smoldering stage
Rx: Prescribed Fire

	Pains Bay Wildfire (Sm)	ARNWR Rx (Fl)	ARNWR Rx (Sm)	PLNWR Rx (Fl)	PLNWR Rx (Sm)
Aldehydes **EPA Method TO-11A/8315 HPLC**					
Formaldehyde	0.384 µg/L	0.066 µg/L	0.011 µg/L	0.061 µg/L	0.005 µg/L
Acetaldehyde	0.404 µg/L	0.038 µg/L	0.005 µg/L	0.035 µg/L	0.016 µg/L
Acrolein & Acetone	<0.001 µg/L	0.011 µg/L	0.004 µg/L	0.013 µg/L	0.009 µg/L
Propionaldehyde	0.236 µg/L	0.014 µg/L	0.002 µg/L	0.003 µg/L	<0.001 µg/L
Crotonaldehyde	<0.001 µg/L	0.002 µg/L	<0.001 µg/L	0.003 µg/L	<0.001 µg/L
Butyraldehyde	<0.001 µg/L	<0.001 µg/L	<0.001 µg/L	0.003 µg/L	0.001 µg/L
Benzaldehyde	0.090 µg/L	0.015 µg/L	0.002 µg/L	0.014 µg/L	<0.001 µg/L
Isovaleradehyde	0.207 µg/L	<0.001 µg/L	<0.001 µg/L	0.003 µg/L	<0.001 µg/L
Valeradelhyde	0.100 µg/L	0.005 µg/L	<0.001 µg/L	0.005 µg/L	<0.001 µg/L
o-Tolualdehyde	0.121 µg/L	0.028 µg/L	0.004 µg/L	0.002 µg/L	<0.001 µg/L
m-Tolualdehyde	<0.001 µg/L	<0.001 µg/L	<0.001 µg/L	0.026 µg/L	<0.001 µg/L
p-Tolualdehyde	0.031 µg/L	<0.001 µg/L	<0.001 µg/L	<0.001 µg/L	<0.001 µg/L
Hexaldehyde	<0.001 µg/L	0.002 µg/L	<0.001 µg/L	0.003 µg/L	<0.001 µg/L
2,5-Dimethylbenzaldehyde	<0.001 µg/L	0.006 µg/L	0.001 µg/L	0.003 µg/L	<0.001 µg/L

Stage: Fl=flaming stage, Sm=smoldering stage
Rx: Prescribed Fire

Pains Bay Fire Levoglucosan

Levoglucosan (LG), a sugar anhydride produced from cellulose combustion, composed a high percentage of $PM_{2.5}$ in the Rx fire smoke. Using the thermal desorption and GC^2 methods of Ma and Hays (2007) on the cyclone and impactor $PM_{2.5}$ filters, we determined that LG accounted for 3 to 10% of total $PM_{2.5}$ mass. Other sugar anhydride compounds (primarily mannosan) composed less than 1% of the $PM_{2.5}$. Cellulose and hemicellulose are susceptible to microbial decomposition and their content in organic soils is considerably lower than that of the original plants (McMahon et al. 1980). This may lead to LG levels in $PM_{2.5}$ from wildfires compared to burning of less decomposed plant tissues. However, our data thus far indicate that LG levels in the soil burning $PM_{2.5}$ is similar to that in $PM_{2.5}$ from aboveground fuels.

Pains Bay Fire Protein

In our Rx smoke studies, protein composition of the PM ranged from 1 to 7% of the PM mass. The background ambient $PM_{2.5}$ samples collected in the absence of smoke contained 0.8% protein. Since much of the organic material in smoke and ambient samples has yet to be identified, protein contributions may warrant further attention, and we are scheduled to analyze

our soil smoke samples for proteins, although a significant degree of protein decomposition can be anticipated as well.

Pains Bay Fire – BlueSky runs and EBAM data

The Pains Bay fire was ignited by lightning on May 5, 2011, on the southern part of ARNWR. It burned both above-ground fuels, and into the deep organics below the surface, generating substantial amounts of smoke that impacted the region, including the community of Stumpy Point on the Dare County peninsula, Roanoke Island, and the tourist destinations on the Outer Banks. In order to quantify health impacts from the smoke, and also to evaluate the BlueSky Smoke Modeling Framework (Larkin et al. 2009), several Met-One, Inc. E-BAM $PM_{2.5}$ monitors were deployed in communities around and downwind from the fire. BlueSky is a modular system that enables several models (fuels, consumption, emission, dispersion, etc.) to run seamlessly to predict emissions and dispersion of smoke from prescribed and wildfires. We have conducted several field campaigns on wildfires in the western U.S. to evaluate BlueSky. Results have shown in some cases BlueSky is biased low compared to observations, and in other cases it is biased high (Strand et al. 2011). Previous BlueSky evaluations have been done at horizontal resolutions of 12 – 40 km, but this is the first time we have been able to use a 1.33 km resolution for our evaluation. This is also the first time we have evaluated BlueSky with fuels typical of deep organic soils in the eastern U.S. Because BlueSky is modular, many different models can be chosen at each step of the pathway. The models we used for this study are shown in Table 1. Note that the meteorological model and fire location model are considered inputs to BlueSky and not part of the framework itself. We are currently analyzing the EBAM observation data and the modeled PM2.5 values from BlueSky, and will present results at the 9th Symposium on Forest and Fire Meteorology in October 2011, and also in a peer-reviewed publication.

BlueSky Gateway modeling system with the BlueSky Smoke Modeling Framework pathway shaded in grey.

Pathname	**Model**
Meteorology	Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model, Version 5 (MM5) v3.7 [*Grell et al.,* 1994]
Fire Information	SMARTFIRE v1 [*Raffuse et al.*, 2009]
Fuel Loading	Fuel Characterization and Classification System (FCCS) [*McKenzie et al.,* 2007]; 1-km gridded data
Total Consumption	Consume v3 [*Ottmar et al.,* 2002]
Rate of Consumption	Fire Emissions Production Simulator v1 (FEPS) [*Anderson et al.,* 2004]
Emissions	Fire Emissions Production Simulator v1 (FEPS) [*Anderson et al.,* 2004]
Plume Rise	The Western Regional Air Partnership (WRAP) method [*Air Sciences Inc.*, 2005]
Surface concentrations	CALPUFF [*Scire et al. 2000*]

The figure below shows the comparison between observations (measured by the EBAMs) at Stumpy Point, which was fairly close to the fire. While most of the observations were between 0 and 1000 µg/m^3, there were some outliers with values greater than 1000 µg/m^3. BlueSky, on the other hand, predicted $PM_{2.5}$ concentrations no higher than 25 µg/m^3. Somewhat farther from the fire, at Manteo, observations never exceeded 1000 µg/m^3, but BlueSky also did not predict such high concentrations, with maximum values just above 50 µg/m^3. This under-prediction is likely due to several reasons. First, point concentrations close to the fire would not be captured by the BlueSky, which is averaging over the grid cell. Second, we know accurately representing the fuels is very important for good consumption estimates. It is possible that BlueSky, which was using the mapped FCCS fuel beds, under-estimated the fuels that were consumed, especially because so much of the organic layer was burning. This would have been missed by BlueSky. Finally, limitations in the models themselves (for example, CALPUFF includes no aerosol chemistry) may have led to the under-prediction. We will continue to analyze the data, and do additional BlueSky simulations with more appropriate fuel beds to gain a better understanding of the model predictions.

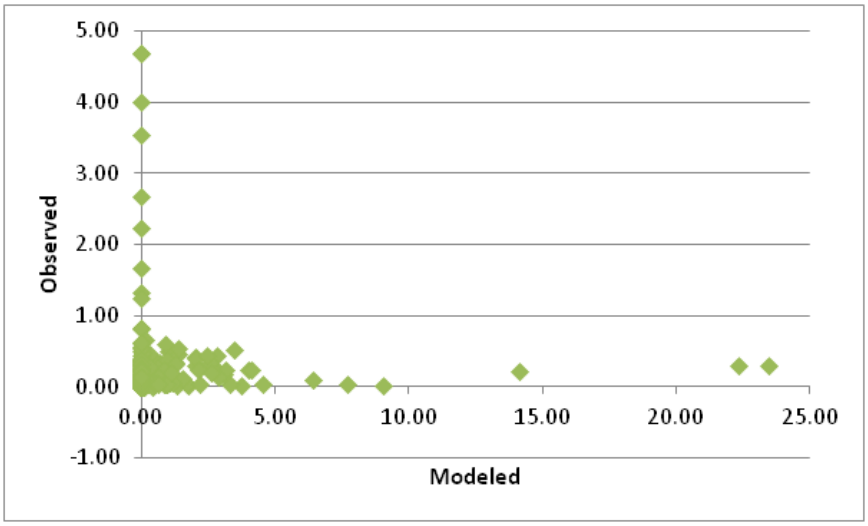


Figure . Comparison of modeled vs. observed $PM_{2.5}$ concentrations at Stumpy Point, NC. Note that the units for the $PM_{2.5}$ observed values are mg/m^3 and the units for modeled values are µg/m^3.

Weather stations and weather data

At the beginning of the project we established two long-term portable weather stations – one at Alligator River National Wildlife Refuge (ARNWR), and one at Pocosin Lakes National Wildlife Refuge (PLNWR). The weather station at ARNWR was deployed within the canopy of a pond pine – pocosin forest and the weather station at PLNWR was located in the open in an area with pond pine, gallberry, and fetterbush. Both weather stations were equipped to measure temperature, relative humidity, wind speed, wind direction, and precipitation amount. They also had the following sensors: fuel stick temperature and moisture, two duff temperature probes, and four duff moisture probes (time-domain reflectometers which provide a relative measure of volumetric moisture content). Three of the duff moisture probes were buried in a pit at depths of approximately 1”, 8”, and 12”, and the fourth was place near the surface in a nearby hummock. One of the duff temperature probes was placed in the pit next to the upper duff moisture probe,

and the other was placed in the hummock next to the fourth moisture probe.
All sensors were connected to a Campbell CR10X datalogger that was powered by a marine battery attached to a solar panel for recharging. We were not able to use cell phone modems to access the data remotely because there was no cell phone coverage were the stations were deployed. Instead we contracted with Airsis, Inc., to develop a satellite modem that could be connected to the datalogger. The satellite modem is the same model used for EBAM and ESAMPLER $PM_{2.5}$ monitors, but new software and a new web page display interface were designed to work with the CR10X datalogger. Typically the satellite modems are used with AC power; however because of the remote locations, we used two marine batteries with two solar panels for recharging. This set-up provided sufficient power for the modem at PLNWR that was in the open with good direct sunlight during the day. The modem at ARNWR, located within the canopy, and with mostly indirect sunlight hitting the solar panels, often did not have enough light to fully recharge the batteries, especially during periods of cloudy weather. Consequently we did not always have access to data from ARNWR in real time. Several trips were made periodically to manually download the data.

Of particular interest was how the duff moisture responded to rainfall and to atmospheric relative humidity. A time series of all four in-ground probes, along with rainfall, is shown in following figures. This period was before a prescribed burn at PLNWR that "escaped" into the organic layer and produced copious amounts of smoke. Both the moisture probe at about 1" depth and the probe just under the surface in the hummock show diurnal fluctuations, indicating they are responding to the diurnal variation in RH, while the deeper probes do not. The shallow and intermediate probes show an increase in moisture content after significant rainfall events, but the deepest probe does not typically respond to rainfall amounts less than about 100 mm.

- In general, moisture content in the organic layer increased rapidly (almost instantaneously) after wetting rainfall, followed by an exponential drying period.
- The upper organic layers respond more rapidly and with a greater magnitude to rainfall than the deeper layers.
- After a wetting rainfall, the organic layers closer to the ground return to their pre-rainfall moisture contents more rapidly than the deeper layers.
- Moisture contents close to the surface respond to diurnal fluctuations in relative humidity.
- Fuel stick moisture responds similarly to that in the organic layer within an inch or two of the surface. This indicates that fuel stick moisture can be used as a proxy for the organic layers in and around hummocks and just below the surface of the ground.

A similar pattern is evident in the data from ARNWR. Prior to the escaped prescribed burn at PLNWR, the duff moisture probes indicated moisture levels near, but not at the lowest levels that had been measured in the previous two to three months. We are still analyzing the data from ARNWR prior to the ignition of the Pains Bay Fire. Unfortunately, the datalogger lost power about two months prior to fire, so we have data only through March 2011. We intend to compare the output from the duff moisture probes at ARNWR to those at PLNWR over the two years period of record to determine if we can use the PLNWR data as a proxy for the ARNWR data in the weeks prior to the Pains Bay Fire.

Figure: PLNWR soil Moisture probes and precipitation

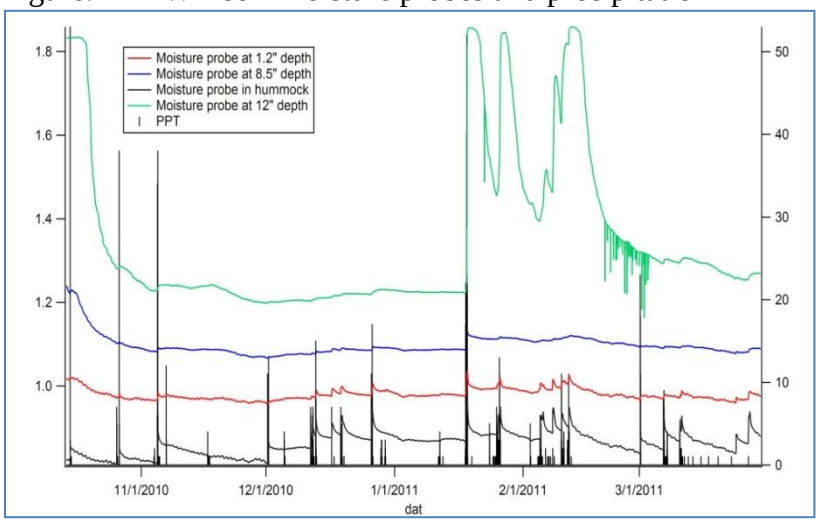


Figure : Time series of soil moisture probes and precipitation

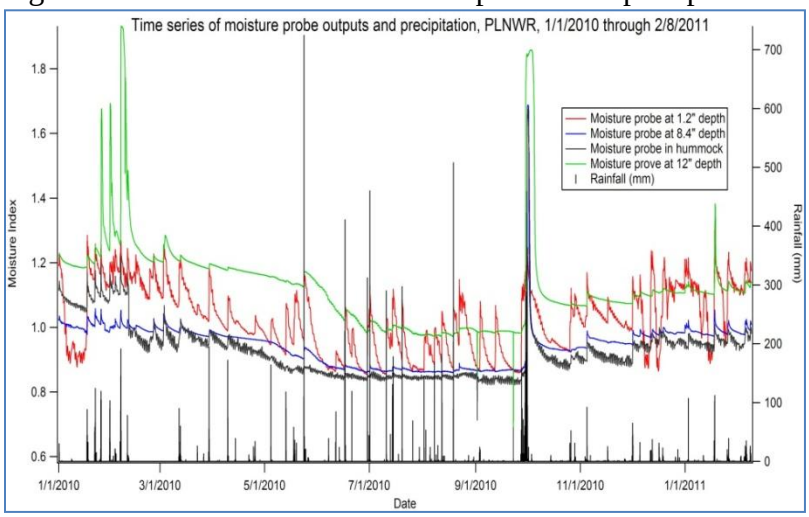
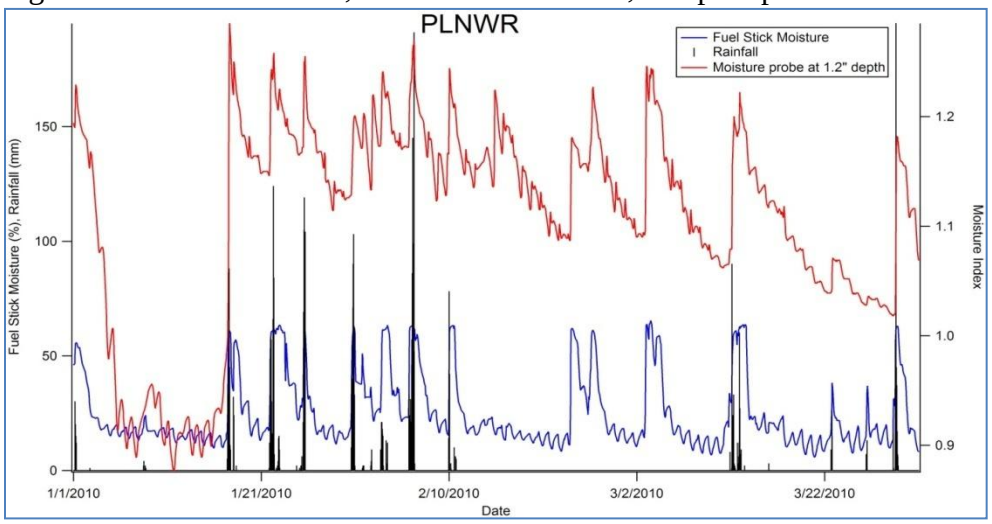


Figure: Ten hour fuel stick, surface soil moisture, and precipitation



Evans Road Fire $PM_{2.5}$ Monitoring

EBam $PM_{2.5}$ monitors were deployed on the Evans Road Fire on June 11th following a June1st lightning ignition. By June 14th the wildfire had reached its near maximum perimeter of 41,059 acres and continued to generate smoke emissions form organic soil combustion until declared out on January 9th, 2009. The United States Environmental Protection Agency (EPA) established National Ambient Air Quality Standards (NAAQS) for particles in the $PM_{2.5}$ size range are able to travel deeply into the respiratory tract, reaching the lungs. Scientific studies have linked increases in daily $PM_{2.5}$ exposure with increased respiratory and cardiovascular hospital admissions, emergency department visits and deaths. Studies also suggest that long term exposure to fine particulate matter may be associated with increased rates of chronic bronchitis, reduced lung function and increased mortality from lung cancer and heart disease. National Ambient Air Standards are established to be protective of public health. The short-term standard (24-hour or daily average) is 35 micrograms per cubic meter of air ($\mu g/m^3$) and the long-term standard (annual average) is 15 $\mu g/m^3$. $PM_{2.5}$ monitoring data from 12 days are illustrated in the table below for 6 monitoring sites in communities surrounding the wildfire. The data illustrates EPA non-compliance of the NAAQS for PM during the active vegetation ignition state of the wildfire which ended on June 14th and the smoke emission from organic soil consumption which dominated PM emissions from June 15th until the wildfire was declares out on January 9th. The values which exceeded the 35 micrograms per cubic meter of air ($\mu g/m^3$) are illustrated in red. Wildfires and their subsequent ignition of organic soils are the predominant source of PM emissions on histosol soils in the southeastern US.

Site	Constituent	Date							
		12-June		13-June		14-June		15-June	
		max ug/m3	hour ending	max ug/m3	hour ending	max ug/m3	hour ending	max ug/m3	hour ending
Belhaven	**PM2.5**	78	12:00	2150	10:00	35	15:00	39	18:00
Columbia	**PM2.5**	37	23:00	60	7:00	532	15:00	297	0:50
Washington	**PM2.5**	60	21:00	1329	10:15	148	10:00	34	23:00
Plymouth	**PM2.5**			32	21:00	32	0:30	30	5:00
Fairfield	**PM2.5**					31	11:00	113	9:00
Manteo	**PM2.5**								
		16-June		17-June		18-June		19-June	
		max ug/m3	hour ending	max ug/m3	hour ending	max ug/m3	hour ending	max ug/m3	hour ending
Belhaven	**PM2.5**	45	06:00	26	11:00	232	01:00	38	21:00
Columbia	**PM2.5**	233	0:00			4428 (PM10)	8:00 6/19	266	01:00
Washington	**PM2.5**	30	2:00, 7:00	34	18:00	66	04:00		
Plymouth	**PM2.5**	35	05:00						
Fairfield	**PM2.5**	479	10:00	168	12:15	65	15:00	556	08:00
Manteo	**PM2.5**	19	20:00	95	21:00	35	23:00	158	10:00

		20-June		21-June		22-June		23-June	
		max ug/m3	hour ending	max ug/m3	hour ending	max ug/m3	hour ending	max ug/m3	hour ending
Belhaven	**PM2.5**	30	06:00	NA	NA	38	08:00	40	19:00
Columbia	**PM2.5**	247	01:00	579	08:00	464	04:00	121	00:00
Washington	**PM2.5**	41	14:45	NA	NA	43	04:00	28	18:00
Plymouth	**PM2.5**	69	13:15	NA	NA	40	06:00	65	20:00
Fairfield	**PM2.5**	406	09:00	NA	NA	48	04:00	105	06:00 6/24
Manteo	**PM2.5**	138	05:00	NA	NA	194	06:00	106	07:00 6/24

Biomass burning in North America is a significant source of photochemically active and radiatively important trace gases as well as PM (Vose et al, 1997, Wiedinmyer et al, 2006). Areas burned in North and Central America can exceed 10 million hectares per year, resulting in trace gas and PM emissions that range from 10 to 40% of total emissions from all sources (Hoezlemann et al, 2004; Wiedinmyer et al, 2006). Residual smoldering combustion (RSC) has been found to produce elevated $PM_{2.5}$ and reduced trace gas emissions relative to flaming combustion (Bertschi et al. 2003). The largest potential pool of carbon vulnerable to RSC is organic soils.

Evans Road Fire Below-Ground Carbon

The majority of the 16,813 ha burn area received the highest dNBR score of 3 (10,700 ha); private and public managed hydrology land cover categories had roughly the same area burned (6100 ha and 6800 ha respectively) and the burned area over public natural hydrology covered 4000 ha (Figure 4). Most of the vegetation burned was high pocosin (14,417 ha); patches of low pocosin existed in the eastern portions of the study area totaling 2,223 ha. Fires burned a relatively small area (173 ha) of agricultural lands along the northern borders.

Belowground carbon emissions ranged from -92 t C ha^{-1}(accretion) in areas of natural hydrology and dNBR = 0 to 1080 t C ha^{-1} in areas of managed hydrology, private ownership and dNBR = 2. The highest carbon emissions was 805 in low pocosin and dNBR = 2 and the lowest measured emission level was 15.5 t C ha^{-1} in high pocosin with dNBR value = 1. The entire study area belowground emissions averaged 545 t C ha^{-1}.

A number of factors affected soil loss due to combustion. Soil loss differed among dNBR categories and ownership/hydrology regime with means ranging from 1 cm to 74 cm; standard deviation for all categories was 0.42 m. ANCOVA (analysis of covariance) results indicate that all factors (drainage, ownership, and dNBR) have a significant effect on pre-post elevation change (dependent variable). These factors explain 34% of the variation in soil elevation change. Tukey-Kramer adjustment for multiple comparisons indicated that managed and natural hydrology as well as private and public ownership had different elevation loss values ($P<0.001$). Pairwise comparisons between mean elevation differences of dNBR categories were significantly different ($P \leq 0.0013$) except for dNBR categories 0 and 1 and dNBR categories 2 and 3.

Figure. Belowground Carbon Emissions in dNBR Categories (t C ha^{-1})

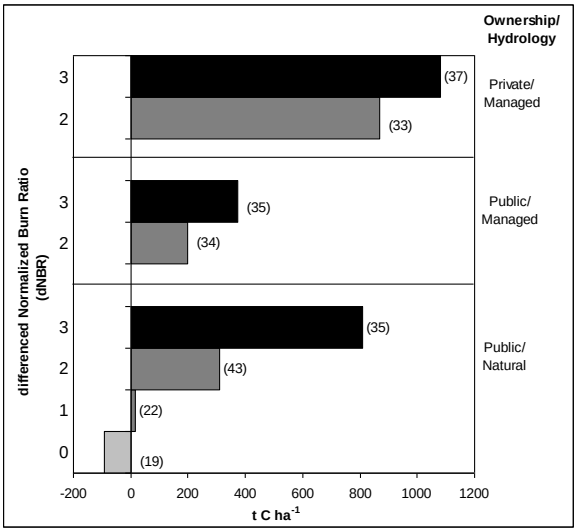


Table. Belowground Carbon Emissions (t C ha^{-1})

Numbers in parentheses indicate field measurement sample size for each class.

dNBR Damage Class	Private Managed Hydrology	Public Managed Hydrology	Public Natural Hydrology
0			-92.13 (19)
1			15.50 (22)
2	1,079.85 (33)	199.75 (34)	310.36 (43)
3	870.43 (37)	373.55 (35)	810.27 (32)

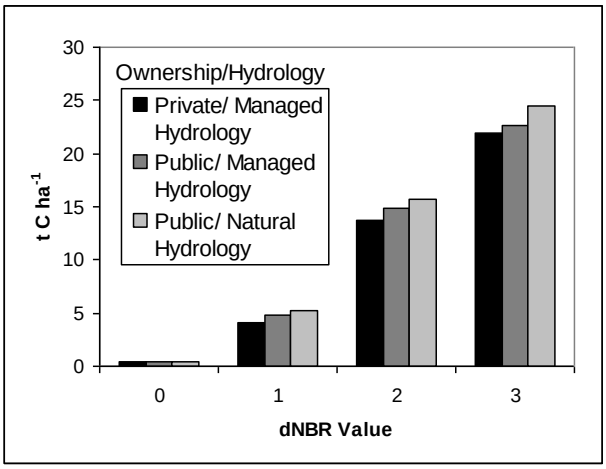
Table. Belowground Carbon Emissions by Land Cover Class (t C ha^{-1})

dNBR Damage Class	High Pocosin	Low Pocosin	Agriculture
0[a]	0	0	[b]
1	15.5	[b]	[b]
2	557.36	805.84	[b]
3	623.79	625.29	[b]

Evans Road Fire Above Ground Carbon Emissions

Aboveground C emissions ranged from approximately 25 T ha^{-1} for the highest damage class, to < 1 T ha^{-1} for the lowest damage class. Differences in t C ha^{-1} in groups sharing the same dNBR value reflect different low and high pocosin fractions among the ownership/hydrology categories. High pocosin vegetation type had the highest fuels and aboveground C emission rate: 24.5 t ha $^{-1}$.

Figure. Aboveground Carbon Emissions by Ownership and Hydrology (t C ha^{-1})



dNBR category 0 indicates limited litter emissions only, category 3 indicates nearly 100% aboveground emissions. Ownership/hydrology values are metric tons of carbon consumed. Average over entire study area = 18.33 t C ha^{-1}. Differences in t C ha^{-1} among groups sharing the same dNBR value reflect different low and high pocosin fractions among the ownership/hydrology categories.

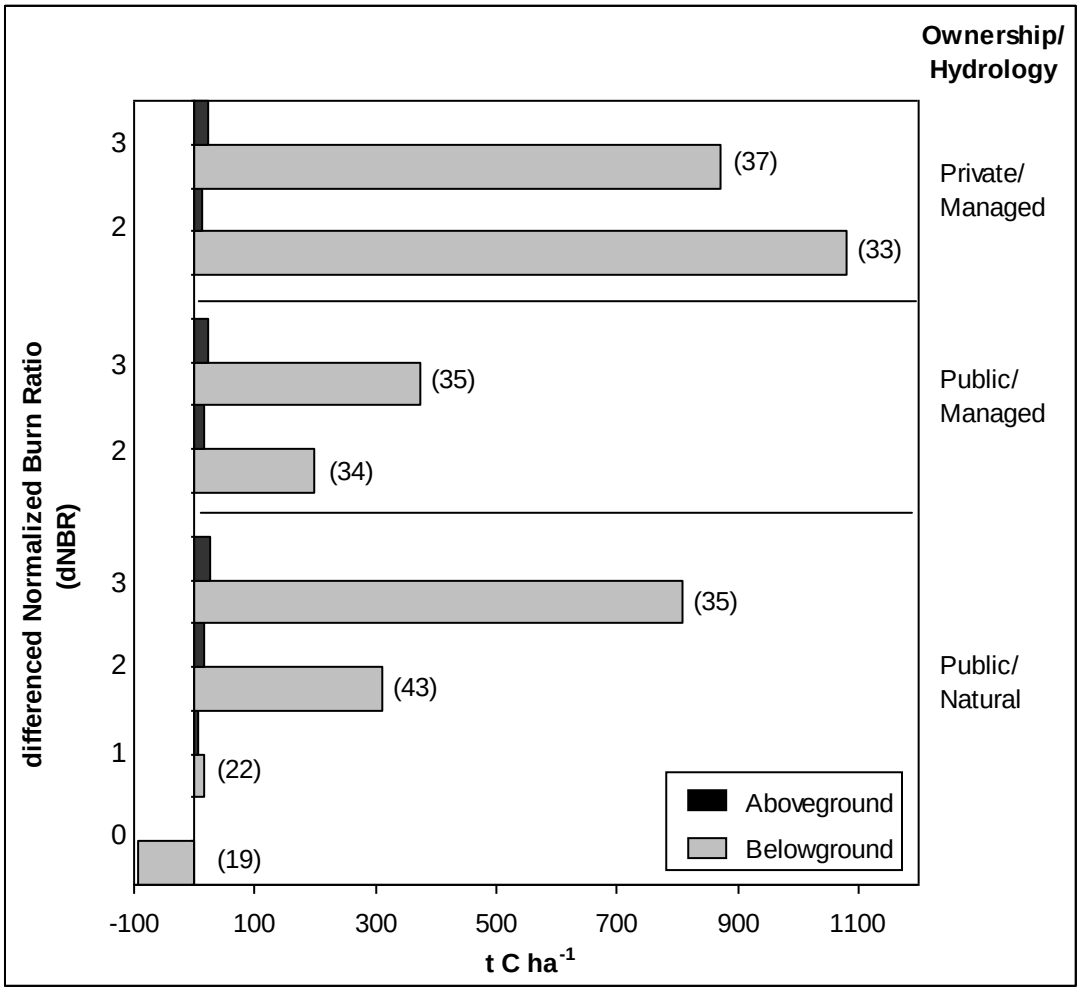
Table. Aboveground Carbon Consumption by Land Cover Class (t C ha$^{-1)}$)

dNBR Damage Class	High Pocosin	Low Pocosin	Agriculture[a]
0	0.43 (litter)	0.27 (litter)	0.45 (crop)
1	5.26 0.86/4.33/0.07 (litter/shrub/foliage)	2.78 0.54/2.24/<0.01 (litter/shrub/foliage)	0.90 (crop)
2	15.78 2.59/12.98/0.2 (litter/shrub/foliage)	8.34 1.61/6.73/0.01 (litter/shrub/foliage)	2.70 (crop)
3	24.47 4.32/19.47/0.68 (litter/shrub/foliage)	12.79 2.68/10.09/0.02 (litter/shrub/foliage)	4.50 (crop)

[a]Fuels burned were crop biomass.

Aboveground C emissions based upon vegetation class incorporated separate calculations for litter, shrub, and foliage in pocosins with areas of taller, thicker vegetation (high pocosins) emitting higher rates of carbon relative to the other two vegetation types . The ecosystem's shrub layer contributed the highest proportion of carbon in dNBR categories 1-3.

Figure Below/Aboveground Carbon Consumption in dNBR Categories 3 and 2 (t C ha^{-1})



Evans Road Fire Mercury Monitoring

An US EPA instrument was deployed on the Evans Road Fire to provide quantitative screening data of ambient mercury concentrations. These data are obtained using a short-term sampling format and quickly and directly indicate the magnitude of ambient mercury concentrations. EPA monitored in about 10 locations on June 12 and June 13 from 2-6 pm. Data were taken at each location for approximately 5 minutes and the highest numbers observed for both "real time" and "10 second average" reported. Comparison data were obtained from the Tekran Mercury Vapor analyzer operated by the North Carolina Division of Air Quality Air Toxics Analytical Support Team (ATAST). The Tekran is a continuous monitor that averages the sample value over a five-minute period. The EPA and ATAST instruments were in good correlation. Short-term, transient, real-time values were highly variable in the 10-50 ng/m3 range apparently changing with smoke density. Ten second averages ranged from 4-23 ng/m3. Tekran values were reasonably consistent at 1-3 ng/m3 until the morning of June 13. When PM values increased to the >1 mg/m^3 range, the Hg vapor concentrations increased to 3-7 ng/m^3. The historic values for Hg vapor in the area have been around 1-2 ng/m^3.

Evans Road Fire Smoke and Cardio-Pulmonary Health Effects

The US EPA National Health and Environmental Effects Research Laboratory assessed the cumulative risk of exposure in 42 contiguous counties adjacent to the Evans Road Fire for a three day window of high PM exposure (June 10-12) and a five days of lagged exposure relative to the non-exposed days. Satellite smoke plume imagery and clinical surveillance were combined to assess the health impacts of wildfire smoke in rural counties in eastern NC. This is the first study to demonstrate both respiratory and cardiac effects following brief exposure to peat wildfire smoke emissions. Consistent with the results from other studies, asthma related outcomes were most prevalent (44% of all respiratory codes considered), especially in adult women (70%) compared to men. Heart failure accounted for 33% of all cardiac events and were substantially more common in individual over 65 (67%) compared with ages 45-65 years. Emergency department visit in exposed counties were significantly increased during the high exposure days and subsequent five day lag period compared to the subsequent six week period. The human health clinical data from Emergency Departments demonstrate an increased percent change in relative risk of 37% associated with the wildfire smoke exposure three day event. The study demonstrates that exposure to smoke from the Evan Road Fire increased Emergency Department visits for asthma, chronic obstructive pulmonary disease (COPD), pneumonia, acute bronchitis, and heart failure in a sparsely populated non-urban area.

V. Management Implications

The United States Environmental Protection Agency (EPA) has implemented new regulations for the management of $PM_{2.5}$, tropospheric ozone, and regional haze. In accordance with sections 108 and 109 of the Clean Air Act (Act), EPA has reviewed the air quality criteria and national ambient air quality standards (NAAQS) for $PM_{2.5}$. Based on these reviews, EPA revised the current primary PM_{10} standards by adding two new primary $PM_{2.5}$ standards set at 15 $\mu g\ m^{-3}$, annual mean, and 35 $\mu g\ m^{-3}$, 24-hour average, to provide increased protection against a wide range of PM-related health effects. These include premature mortality, increased hospital admissions and emergency room visits, increased respiratory symptoms and disease, decreased lung function, and alterations in lung tissue and structure and in respiratory tract defense mechanisms. Fire generates CO, $PM_{2.5}$, and ozone precursor gases that reduce visibility. Hence, natural area and agricultural land management, nationwide, may come under increased scrutiny as regulators seek reductions in pollutant emissions which contribute to NAAQS violations. Current guidelines allow flexibility in application of prescribed burning in smoke-sensitive areas if burn prescriptions are adhered to.

Little information is currently available on the trade-offs between prescribed burning and wildfire on organic soils in the US. The use of fire and the importance of this issue in particular is likely to increase in the future. Our data, when examined in the context of other studies, suggest that emissions of $PM_{2.5}$ and PM_{10} and gas phase reduced compounds, (many of which are air toxics) will be lower during prescribed fires compared to wildfires covering the same area. This is suspected largely because it is known that wildfires occur typically during excessively dry periods, when much of the forest floor and heavy debris are dry and susceptible to smoldering incomplete combustion, the source of many toxic compounds. These wildfires may increase fuel consumption by an order of magnitude or more since soil and heavy fuels can be consumed under these dry conditions. In addition, emissions factors for PM and reduced trace gases may be 2 to over 10 times higher from these soil and heavy fuels. This study (McMahon et al, 1980; Bertschi et al, 2003; and Chen et al. 2007) compared to the lighter fuels consumed during Rx burns. Amounts of smoke may therefore be many times higher per acre than emissions

from prescribed burns. In addition, human exposure to fire and smoke is likely to be much greater during wildfires since ventilation and other factors influencing smoke dispersion cannot be coordinated with wildfire as they can with Rx burning. Wildfires in southeastern peat soils also may smolder beneath the surface and re-ignite without detection. These subsurface fires are dangerous to firefighters and others present on the landscape. Long-term ecosystem damage may result from southern wildfires. In Southeastern U.S. forests this can mean damage to red cockaded woodpecker nest trees, habitat which can take many decades to restore. This habitat has been reduced by over 97% due to land management practices since the 1700s, placing the RCW and other species such as the gopher tortoise in endangered status.

Our data, when combined from both projects, suggests Rx fire may reduce air emissions due to high fuel accumulations, and also reduce the risk and spread of wildfire along with its risk of prolonged ground fires. It appears likely that burning under prescription will reduce 1) human exposure to and emissions of hazardous air pollutants, 2) net risk to property and human welfare, and 3) damage to critical (RT&E) wildlife habitat by reducing wildfire and associated soil consumption hazards.

VI. Relationship to Other Recent Findings

The contribution of global biomass burning to emissions of carbon to the atmosphere was identified as an important source of radiatively and photochemically reactive trace gases in 1980 (Seiler and Crutzen, 1980). A previous study (Crutzen *et al.* 1979) had investigated the atmospheric budgets of trace gases in the atmosphere which including carbon monoxide (CO), molecular hydrogen (H_2), nitrous oxide (N_2O), nitric oxide (NO), nitrogen dioxide (NO_2), and carbonyl sulfide (COS). Seiler *et al.* (1980) showed that these trace gases were emitted into the atmosphere in large quantities by measuring emission rates of trace gases relative to carbon dioxide (CO_2) in the smoke plumes of forest and grassland wildland fires. Global emission rates of trace gases were approximated from CO_2 released into the atmosphere during global wildfires and prescribed burning across different ecosystems. Seiler and Crutzen (1980) used a general model to estimate the biomass burned annually in global biomes which consisted of total land area burned, the average organic matter per unit area, the average above-ground biomass relative to the total average biomass, and the burning efficiency of the above-ground biomass. They calculated annual global C emissions of 2-4 Pg C. This model did not include the contribution of soil C emitted during wildland fire, which Wong (1978) estimated at 400Tg C yr^{-1} and Seiler and Crutzen (1980) revised downward to 100 Tg C yr^{-1}. A recent study (van der Werf *et al.* 2010) excluded fuelwood burning from the C emissions estimate of Seiler and Crutzen (1980) and calculated annual global C emissions of 2.6 Pg (ranging from 1.7-3.5 Pg C). The fire C emissions budget was allocated to agricultural waste burning (33%), shifting agriculture (29%), savanna region wildfires (21%), deforestation (12%), temperate region wildfires (4%), and boreal region wildfires (1%).

Recent advance in satellite-derived fire products using the MODerate resolution Imaging Spectroradiometer (MODIS) data from the Terra and Aqua satellites, the Advanced Very High Resolution Radiometer (AVHRR) sensor on the National Oceanic and Atmospheric Administration (NOAA) Polar Operational Environmental Satellite (POES), and the Geostationary Operational Environmental Satellite (GOES) to quantify burned area in near-real-time has enhanced the ability to estimate regional and global fire emissions (Gregoire et al., 2003; Simon et al, 2004; Giglio et al., 2006). Remotely sensed data and their products have been used in combination with biogeochemical and terrestrial ecosystem models to estimate emissions

(Hoelzemann et al., 2004; Ito and Penner, 2004; Jain et al., 2006; van der Werf et al., 2003, 2004, 2006). These studies estimated annual global wildland fire carbon emissions that ranged between 1 and 3 Pg C, with large interannual variability associated with global fire activity and ~20% uncertainty (Field and Shen 2008, van der Wert *et al.* 2010). Wildland fire C emission uncertainties were highest in boreal, temporate, and equatorial Asia ecosystems due to the lack of accurate field measurements and satellite observations in estimating the fuel consumed during long duration organic soil fires. Uncertainties in estimation of deforestation and burned area, fuel loading, and combustion efficiency were likely sources of underestimation of global C emissions (van der Wert *et al.* 2010).

Determining the magnitude and spatial of C storage in boreal, temporate, and equatorial Asia ecosystems peatlands is an important first step towards predicting C emissions during wildland fires and the changes in regional carbon balance in response to climate change. Global peatlands comprise approximately 3% of the earth's land area and store an estimated one-third of the global organic soil C stocks. Soil organic C is estimated to be 684–724 Pg in the upper 30 cm, 1462–1548 Pg in the upper 100 cm, and 2,376–2,456 Pg in the upper 200 cm (Batjes 1996). Boreal and subarctic peatlands comprise a carbon pool of 455 Pg (Gorham 1991) to 547 Pg (Yu *et al.* 2010), Southeast Asia peatlands store 42 Pg C (Hooijer *et al.* 2010), and South American peatlands have accumulated 15 Pg C (Yu *et al.* 2010). The spatial heterogeneity of peatland soils and vegetation poses challenges to quantifying C storage and emissions, and estimating interannual variability and uncertainty.

The global area of temperate peatlands is estimated at 0.19 to 0.88 million km^2 (Matthews and Fung 1987, Poulter *et al* 2006). In the continental United States, temperate peatlands are found primarily in the Great Lakes region in hardwood forest and non-forested ecosystems, and in the coastal plain of the Southeastern and Gulf states. The reported total C stored in temperate peatlands in one field study in northern Minnesota, USA was 1,286 ±125 Mg C ha^{-1}, with 90–99% of that C found in peat soils that ranged from 1 to 5 m in depth (Weishampel *et al.* 2009). In North Carolina, the total area of peatland soils is 2,700 km^2 and the total C pool is calculated at 327 Tg (Ingram and Otte 1981).

Wildland fire emissions in the continuous United States vary considerably year to year, with average annual carbon releases estimated at 58 Tg (Wiedinmyer and Neff 2007). Examinations of surface fires have attributed approximately two-thirds of the fire extent and emissions in the southeastern United States to prescribed fires (Wiedinmyer and Neff 2007, NIFC 2010). However, wildfires that ignite organic peat soils in this geographic region are frequent phenomena when drought conditions prevail. In North America, modeling efforts in boreal regions have addressed ground fire contributions to carbon emissions but temperate peat fires have received much less attention (Poulter et al. 2006, de Groot et al. 2007, de Groot et al. 2009).

VII. Future Work Needed

- Field studies are needed to better characterize the contributions of vegetation and organic soil C emissions for Rx and wildland fires. There has been little data collected during and following organic soil ignitions to quantify the C and emission contributions from the fires.
- Human health impacts form long duration organic soil fires were identified as an important public health concern. Future research is needed to determine the public's

exposure to smoke and VOC/aldehyde emissions and the impacts of these emissions on increased respiratory and cardiac hospital admissions. Emissions samples need to be designed for spatial and temporal sampling at nearby communities to determine ground exposures and the transport of PM and VOCs/aldehydes in short and long range transport.

- The BlueSky framework needs to be parameterized to account for the large organic soil emissions vs. vegetation emissions during Rx and wildfire events to improve the models predictive accuracy and precision. This is especially important for fires adjacent to sensitive infrastructure and communities.
- Additional data is needed to better characterize the differences in emission factors between Rx burns and wildfire events.
- Wildifires on organic soils pose unique challenges to managing vegetation and wildlife following fires. Little is understood on planning and implementing vegetation and wildlife rehabilitation following long duration organic soil wildfires.
- There is a need for better spatial sampling of meteorology data prior to, during, and after organic soil Rx burns and wildfires. Spatial heterogeneity across landscapes with organic soils pose unique challenges to quantifying fire behavior variables at burn tract to county scales.

VIII. Deliverable Crosswalk Table

Deliverable	Description	Status
Refereed Publication	Peer reviewed publications in years 1 and 2	Submitted or in progress
Non-Refereed Publication	Conference proceedings in years 1-2	Completed
Conference/Symposia/Workshop	Host RX workshop annually at FMO meetings	Completed
Field Demonstration/Tour	Field research site tours of burn sites	Completed
Invited Paper/Presentation	Papers at two conferences in years 1-2	Completed
Poster	Posters at two conferences in years 1-2	Completed
Training session	BlueSky modeling framework training	Completed
Computer Model/Software/Algorithm	BlueSky model updates for southeast FCAMM	Completed
Dataset (including spatial)	BlueSky model output	Completed
Dataset (including spatial)	GIS and remotely sensed data of burns	Completed
Website	Project website with research data, photos, videos	Completed and ongoing updates
Final Joint Fire Science Report	Final project summary and deliverables	Completed

Refereed Publication

- Geron, C. 2009. Carbonaceous aerosol over a Pinus taeda forest in Central North Carolina, USA. Atmospheric Environment 43: 959-969.
- Geron, C., Mickler, R.A., Stephenson, G., Bowling, M. Air Emissions from Prescribed Burning on the Coastal Plain of North Carolina (In submission progress)
- Mickler, R. A., D. Welch, and A.D. Bailey. 2011. Carbon dynamics of wildfire on organic soils of the coastal plain of North Carolina. Int..J. Wildland Fire (In submission process).
- Mickler, R.A. and D. Welch 2011. An estimate of above- and below-ground carbon emissions from peatland shrub and forest ecosystems in North Carolina. J. Geophys. Res. (In submission process)
- Evaluation of the BlueSky Smoke Modeling Framework During a Wildfire in Deep Organic Soils. (In progress)
- Comparison of Meteorological and Duff Moisture Data collected at two locations in eastern North Carolina. (In progress)
- Comparison of fuel EFS with above-ground vegetation and organic soil smoldering. (In progress)

Non-Refereed Publication

Conference Proceedings for:

- 4th International Fire Ecology and Management Congress, November 30, 2009, Savannah, GA
- 3rd Fire Behavior and Fuels Conference (International Association of Wildland Fire), October 28, 2010, Spokane, WA
- Ninth Symposium on Fire and Forest Meteorology,18–20 October 2011, Palm Springs, CA

Conference/Symposia/Workshop

- 4th International Fire Ecology and Management Congress, November 30, 2009, Savannah, GA
- 3rd Fire Behavior and Fuels Conference (International Association of Wildland Fire), October 28, 2010, Spokane, WA
- Ninth Symposium on Fire and Forest Meteorology,18–20 October 2011, Palm Springs, CA

Invited Paper/Presentation

- BlueSky Updates. Miriam Rorig. 2010 Annual Burn and Smoke Management Meeting, April 12-14, 2010, Ceour d'Alene, ID
- BlueSky-enabled smoke tools. 3rd Fire Behavior and Fuels Conference (International Association of Wildland Fire), October 28, 2010, Spokane, WA

Posters

- 4th International Fire Ecology and Management Congress, November 30, 2009, Savannah, GA
- 3rd Fire Behavior and Fuels Conference (International Association of Wildland Fire), October 28, 2010, Spokane, WA
- Ninth Symposium on Fire and Forest Meteorology,18–20 October 2011, Palm Springs, CA

Training Session:

- BlueSky ,Burn Boss Refresher Training, Denver, CO, January 26, 2010
- Smoke and Air Quality Management Tools Training, 3rd Fire Behavior and Fuels Conference (International Association of Wildland Fire), October 25, 2010, Spokane, WA.
- WFDSS Smoke Webinar to DOI/BLM, 30 November 2010.
- AirFire Overview and BlueSky Tools. Presentation to visiting scientists from the Korea Forest Service and Korea Forest Research Institute, September 13, 2010, Seattle, WA.

Computer Model/Software/Algorithm

- BlueSky modeling framework updates at USDA Forest Service AirFire Team, Seattle, WA. Contact: Tara Strand**,** U.S. Forest Service AirFire Team**,** Tara Strand (at) fs.fed.us

Dataset – BlueSky Output

- BlueSky modeling framework output for project Rx and wildfires archived at USDA Forest Service AirFir Team, Seattle, WA.

Dataset – GIS/Remote Sensing Output

- GIS/Remote sensing project data available for project Rx and wildfires archived at Alion Science and Technology, Durham, NC, Contact: Robert Mickler, rmickler@alionscience.com

Website

- BlueSky website: www.airfire.org

IX. References

Anderson, J.R., Hardy, E.E., Roach J.T., and Witmer R.E., 1976, A land use and land cover classification system for use with remote sensor data: U.S. Geological Survey Professional Paper 964, 28 p.

Andreae, M.O. and Merlet, P. 2001. Emission of trace gases and aerosols from biomass burning. Global Biogeochemical Cycles 15(4): 955-966.

Bertschi, I., R. J. Yokelson, D. E. Ward, R. E. Babbitt, R. A. Susott, J. G. Goode and W. M. Hao 2003.Trace gas and particle emissions from fires in large diameter and belowground biomass fuels Journal of Geophysical Research 108(D13): 1-12.

Brown, J.K., R.D. Oberheu, and C. M. Johnston. 1982. Handbook for inventorying surface fuels and biomass in the interior west. USDA Forest Service, GTR INT-129, Ogden, UT.

Chen, F.-L., R. Williams, E. Svendsen, K. Yeatts, J. Creason, J. Scott, D. Terrell and M. Case 2007.Coarse particulate matter concentrations from residential outdoor sites associated with the North Carolina Asthma and Children's Environment Studies (NC-ACES) Atmospheric Environment 41(6): 1200-1208.

Fowler, C.T. 2003. Human Health Impacts of Forest Fires in the Southern United States: A Literature Review. Journal of Ecological Anthropology 7:39-59.

Grell, G.A., J. Dudhia, and D.R. Stauffer, 1994: A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5). NCAR Technical Note NCAR/TN-398+STR, December, 1994.

Hao, W. M. and M. Liu (1994). Spatial and temporal distribution of tropical biomass burning. Global Biogeochemical Cycles 8(4): 495-503.

Hays, M. D., C. D. Geron, et al. (2002). Speciation of Gas-Phase and Fine Particle Emissions from Burning of Foliar Fuels. Environmental Science and Technology 36(11): 2281-2295.

Larkin, N.K., S.M. O'Neill, R. Solomon, S. Raffuse, T. Strand, D. Sullivan, C. Krull, M. Rorig, J. Peterson, and S.A. Ferguson, 2009: The BlueSky Smoke Modeling Framework. *Int. J. Wildland Fire*, **18**, 906-920.

McMahon, C.K., Wade, D.O., and Tsoukalas, S.N. 1980. Combustion Characteristics and Emissions from Burning Organic Soils. 73rd Annual Meeting of the Air Pollution Control Association, Montreal, Quebec, June 22-27, 1980

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

Menetrez, M.Y., Foarde, K.K. Dean, T.R., Betancourt, D.A., and Moore, S.A. 2007. An evaluation of the protein mass of particulate matter. Atmospheric Environment 41(37): 8264-8274.

Ottmar, R. D., S. J. Prichard, R. E. Vihnanek, and D. V. Sandberg (2002), Modification and validation of fuel consumption models for shrub and forested lands in the Southwest, Pacific Northwest, Rockies, Midwest, Southeast, and Alaska. Final report, Joint Fire Science Program Project 98-109-06.

Ryan, K.C. and N.V. Noste. 1985. Evaluating prescribed fires. In: J.E. Lotan, B.M. Kilgore, W.C. Fischer, and R.W. Mutch, Tec. Cord. Proc. Symposium and Workshop on Wilderness Fire. USDA Forest Service General Technical Report. INT-182. Intermountain Forest and Range Experiment Station, Ogden, UT. Pp. 230-238.

Scire, J.S., D.G. Strimaitis, and R.J. Yamartino, 2000: A User's Guide for the CALPUFF Dispersion Model (Version 5). Earth Tech Inc., 196 Baker Avenue, Concord, MA, 01742.
Strand, T.M., N. Larkin, R. Solomon, M. Rorig, K.J. Craig, S. Raffuse, D. Sullivan, N. Wheeler, and D. Pryden, 2011: Analysis of $PM_{2.5}$ predictions during the 2007 southern and 2008 northern California fires. Submitted to *J. Geophys. Res.*

Taylor, J. A. and P. R. Zimmerman (1991). Modeling trace gas emissions from biomass burning. MIT Press (Chapter 41): 345-350.

Trent, A. (2003) Laboratory Evaluation of Real-Time Smoke Particulate Monitors USDA Forest Service Report 0325-2834-MTDC: 1-14.

Vose, J. M., W. T. Swank, et al. (1997). Emissions from forest burning in the Southeastern United States: Application of a model determining spatial and temporal fire variation. Biomass Burning and Global Change. J. S. Levine. Cambridge, MA, MIT Press. 2: 733-749.

Ward, D. E. and C. C. Hardy (1988). Organic and elemental profiles for smoke from prescribed fires. APCA/EPA conference "Receptor Models in Air Resource Management" San Francisco, CA.

X. Acknowledgments

We are very grateful to Xindi Bian, USDA Forest Service, Northern Research Station, East Lansing, MI, for providing us with MM5 model output at 1.33km resolution for use in the BlueSky Framework.