Development and Demonstration of Smoke Plume, Fire Emissions, and Pre- and Postprescribed Fire Fuel Models on North Carolina Coastal Plain Forest Ecosystems

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***Abstract**—Wildland fuels have been accumulating in the United States during at least the past half-century due to wildland fire management practices and policies. The additional fuels contribute to intense fire behavior, increase the costs of wildland fire control, and contribute to the degradation of local and regional air quality. The management of prescribed and wildland fire on Federal, State, and private lands pose critical challenges for the characterization of preburn fire fuels and postburn carbon consumption assessments, predicting smoke trajectories and concentrations, and modeling air quality emissions. Prescribed and wildland fires are both important sources of airborne fine particulate matter ($PM_{2.5}$) and ozone (O_3) precursors such as nonmethane volatile (VOCs) and semivolatile organic compounds (SVOCs), nitrogen oxides (NO_x), carbon monoxide (CO), and methane (CH_4). We quantified pre- and postburn belowground and aboveground biomass to determine fuel consumption for fine and coarse woody material, shrub, herbs, litter, and duff, and assessed fire effects on plant communities. The BlueSky smoke prediction modeling framework, and the BlueSky Rapid Access Information System (BlueSkyRAINS) were implemented to model smoke trajectory and $PM_{2.5}$ concentrations at ground level in the downwind smoke plume. $PM_{10\ and\ 2.5}$ and photochemically and radiatively important trace gases during the flaming and smoldering stages of prescribed burns were characterized and fire emission modeled to determine emission factors for chemical species.*

Introduction

Fire has played a major role in determining the distribution of plants across the Coastal Plain of the Southeastern United States. The extent of fire dependent ecosystems has been reduced as a result of fire exclusion and landuse conversion. Wildland fire fuel loading throughout the United States has become a hazard to life, property, ecosystem health, and the habitat of threatened and endangered species as a result of past fire exclusion policies and practices. Land managers are concerned that fuel loads are reaching hazardous levels that can lead to widespread catastrophic wildfires in forest ecosystems and the wildland/urban interface. This wildland fire risk is currently impacting ecosystem management planning throughout the Southeast.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

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Measurement and Modeling of Down Woody Debris and Fuels

Fuel classification during the past 75 years 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 using 13 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 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 these limitations are currently being addressed by a fuel characteristic classification (FCC) (Sandberg and others 2001).

The availability of fire-spread models has increased the need for quantitative fuel field data. A line-intersect method developed by Brown and others (1982) has been widely adopted to quantify fuel-loading inputs. The USDA Forest Service Forest Inventory and Analysis (FIA) program recognized the need for extensive information on fuels across the landscape. Fuel field protocols (http://fia.fs.fed.us/library/field-guides-methods-proc/) were piloted by the former Forest Health Monitoring Program between 1998 and 2000, and implemented in 2001 on a 1/16th subset of the standard base FIA grid plots. FIA methods generally partition the forest ecosystem into pools for live trees, down deadwood, standing dead trees, understory vegetation, forest floor materials, and soil. Estimating site-specific fuels from this database has been particularly problematic. The data are not consistently available from the FIA inventory data source and there are little data on fuel loading in the scientific literature. Additionally the biomass algorithms are based nationally on available data collected regionally for tree, shrub, and herbaceous species and associated wood density for decay classes.

Past fuel and fire behavior research has resulted in only qualitative measures of fuel loads and rates of spread. A more detailed fuel classification, based on species composition, standing dead and down deadwood, fuel size classification, understory vegetation, and vertical distribution of fuels, would have much more utility than the broad fuel model classification system now in use. Fire in the deep organic soil areas of the Coastal Plain is frequently associated with costly blowup wildfires and soil fires started from prescribed fire fuel reduction and habitat management burns. Wildfires in this area can, under certain combinations of fuel and weather, grow from a low intensity burn to a virtually uncontrollable burn until weather conditions change or the fire has run out of fuel. 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. A better understanding of the behavior of fires and the role of fuel loading in fire behavior will contribute to the control of wildfires and the use of prescribed fire as a management tool in the region.

Fire Emissions Monitoring and Emission Factor 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 and total emissions of trace gases and PM from individual fires are typically determined using a carbon mass balance approach as described in Ward and Hardy (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. These approaches have been used to calculate emission factors (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 for the calculation of 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.

For wildfire sampling, remote platforms are needed to access smoke plumes. This is necessary to maintain safe working conditions and ensure that samples are collected in air parcels dominated by the fires. Ground based sampling is not practical for wildfire studies because adequate planning horizons or sampling sites are not typically available. Even when sites are located, shifting winds often move smoke away from sampling systems. Manned aircraft has been used to collect smoke samples in the past, but this is dangerous and can be prohibitively expensive.

Biomass burning in the Southeast can be a potentially significant source of photochemically active and radiatively important trace gases as well as PM (Barnard and Sabo 2003). Areas burned in the region vary annually but are typically several million acres per year, resulting in trace gas and PM emissions that range from 2 to 15 percent of total emissions from other sources. Little data on emissions from prescribed burning are currently available, and this fire type in particular is projected to increase in the Southeastern United States. Emissions of reduced compounds, many of which are air toxins, are thought to 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 is dry and susceptible to smoldering incomplete combustion, the source of many toxic compounds.

Continuous monitoring of O_3, PM, and 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 to 150 percent) pollution levels than seasonal median values have been documented (Cheng and others 1998). While fire events can cause high transient air pollutant concentrations, for most criteria pollutants, the fire emissions are a relatively small fraction of the annual emission inventory. For fine PM, however, the annual emission estimates from biomass burning represent a significant fraction of many Southern States' emission inventories, especially in the counties where the emissions are concentrated (Dennis and others 2002). Given the current emphasis by the EPA on particles, it is imperative that real-world emission data be developed from open burning sources.

It is generally thought that emission factors 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, especially where smoldering combustion is important, EFs are still quite uncertain (Andreae and Merlet 2001; Hays and others 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, litter, and organic soils. These fuels are important in our proposed study area. Limited observations suggest that RSC is a globally significant source of emissions to the troposphere (Bertschi and others 2003). These authors used a model that predicts trace gas EF for fires in a wide variety of aboveground fine fuels. It failed to predict emission factors for RSC. For many compounds, the EF for RSC-prone fuels is different from the EF for the same compounds measured in fire convection columns above forest ecosystems. Some large changes resulted in estimates of biomass fire emissions with the inclusion of RSC. For instance, EF increases by a factor of 2.5 even when RSC accounts for only 10 percent of fuel consumption. This shows that many more measurements of fuel consumption and emission factors for RSC are needed to improve estimates of biomass burning emissions.

Smoke Trajectory and Concentration 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 the 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 the Coastal Plain of the Southeast. Many of the dispersion models in use by wildland mangers today—SASEM (Sestak and Riebau 1988), VALBOX (Sestak and others 1989), VSMOKE (Lavdas 1996), NFSpuff (Harison 1995), TSARS (Hummel and Rafsnider 1995), and CALPUFF (Scire and others 1995)—have been adapted from industrial stack models for use in wildland fires. Smoke models for prescribed burning differ from point-source industrial models due to additional data requirements for pattern of ignition, fuel moisture by size, fuel loading by size, fuel distribution, and local weather that influences burn rates and dispersion. 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. FARSITE does not model smoke dispersion, but output from the combined models can now be used in smoke dispersion models.

The BlueSky smoke modeling framework (http://blueskyrains.org) 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 and others 2003, 2005). BlueSky is currently functional over the conterminous United States. While differences exist regionally, each night BlueSky obtains regional meteorological predictions and reported burn information from available private, State, and Federal agencies, merges these data with models of fuel consumption and emissions, and processes dispersion and trajectory models to produce regional estimates of smoke concentrations for the next 1 to 3 days (Ferguson and others 2001). Smoke and fire managers access these predictions via the internet as a tool to aid their "go/no-go" decisions for burning operations and other real-time decision support (Ferguson and others 2003).

Methods

Vegetation Classification and Pre- and Postburn Biomass

We acquired 2004 leaf-off color infrared (CIR) negatives of stereo aerial photography for study areas and collected field data on fuel loads and/or fuel accumulation. Aerial photos were scanned to generate digital data layers and stereo models for interpretation as well as orthorectified mosaics of the study areas. We incorporated existing GIS vegetation data from the U.S. Fish and Wildlife Service and the U.S. Air Force using onscreen stereoscopic techniques to create a digital vegetation database. Vegetation was classified to the Alliance level using the National Vegetation Classification System (http://biology.usgs.gov/npsveg/nvcs.html). Field plots were randomly assigned within each vegetation Alliance. Fire fuel data from field based sample plots, digital photos, and vegetation data were used to develop fire fuel polygons. Additional field data were used to assess the thematic accuracy of the vegetation classification, the positional accuracy of the digital orthophoto mosaic, and the fuel load polygons. Metadata were created for the digital orthophoto mosaics and vegetation and fuel load databases.

We established a permanent plot network on the Alligator River National Wildlife Refuge and the Air Force Dare County Bombing Range modeled on USDA Forest Service FIA P2 and P3 plots to measure and characterize live biomass and pre- and postburn down deadwood (DWD). We used field protocols based in methods establish by the USDA Forest Service in "Field Instructions for Southern Forest Inventory." The collection of DWD data was collected using a line-intersect method to sample down wood along linear transects based on Brown's transects (Brown and others 1982). Plot-level data on the amount, distribution, and characterization of DWD were related to the detailed attribute data for other ecosystem components on the same plot—that is, shrub and herbaceous understory, live and dead herbs (including grasses), and litter. FIA methodology was augmented with additional data on the vertical distribution of DWD for input into the FARSITE fire behavior model. 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 to 0.9 inch, and large = 1 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 at the 24-ft location on each transect. FIA cluster subplot design with three 24-ft. transects (slope corrected, horizontal distance) were established at each subplot location. All subplot clusters were laid out in a fixed pattern regardless of different condition classes and only the transect segments that fell in the forest condition being sampled. The 6.8-ft radius micro plots were used to estimate the percent cover and height of live and dead shrubs, live and dead herbs (includes grasses) and litter.

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. Biomass computations for each fuel class have been previously developed in a pond pine/high pocosin forest type. Fuel class biomass algorithms were developed for additional forest species and decay classes in the forest type. Additional micro plots were established for destructive sampling of shrub and herbaceous vegetation to develop biomass equations. Previous equations were developed primarily for Western U.S. species (Brown and others 1982).

Prescribed Burning Emissions Monitoring and Modeling

In order to assess emissions of fine PM from prescribed fire, we investigated emissions from this burning practice during the course of prescribed burns for the fall and spring of 2005 and 2006. Mass balance techniques were used to support flux measurements of dioxin, methyl chloride, methyl bromide, and other compounds. Grab samples—stainless steel canisters for trace gases, filter packs for PM, and polyurethane foam traps for semivolatiles (Hays and others 2002)—were collected in the plumes of the fire during both flaming and smoldering conditions. These samples were then subjected to particle and total gaseous carbon analysis using a thermo-gravimetric analysis and gas chromatography/mass spectroscopy (GC/MS). Total emissions were determined by multiplying emission ratio by the estimate of total fuel carbon consumption. Total fuel carbon by mass is approximately half of the fuel dry weight following the general cellulosic molecular formula of $C_6H_9O_4$.

We sampled air that had cooled to approximately ambient temperature (within 100 m of the fire) to allow partitioning of semivolatiles between the gas and aerosol phase. We sampled directly through $PM_{2.5}$ cyclones using high volume pumps, onto 47 mm quartz (for organic PM components) and Teflon filters (for inorganic ions and elements). These were backed by polyurethane foam plugs for quantitative analysis of semivolatile organic compounds that pass through or are volatilized from the filters. Trace gases (methane, C^2-C^{12} VOC) were characterized separately using Summa stainless steel canisters and GC/MS. Target compounds in the gas and PM phase included saturated (alkane) and unsaturated hydrocarbons, aldehydes, ketones, organic acids, and polycyclic organic hydrocarbons (PAH). We also measured CO via gas filter correlation (Teco 46C) and CO^2 via infrared gas techniques (Licor 7000) to characterize carbon fluxes for the mass balance flux techniques and to characterize the nature of plume dispersion and proximity to the combustion. We used the CO/CO^2/VOC measurements to help us in chemically identifying the flaming and smoldering stages of the fires.

We quantitatively analyzed these samples to determine emission factors for individual trace gases. These were compared with factors from other fuel types. We also compared current source apportionment chemical fingerprints from these fires with those from our laboratory and "burnhut" studies (Hays and others 2002). This allowed us to assess these signatures with *in situ* data. We compared emission factors and fluxes with any available data from wildfire emissions from corresponding forest types.

Smoke Modeling

A forecast of expected weather and smoke behavior was developed before each experimental prescribed burn. On-site meteorological information was gathered to enable a run and test the BlueSky smoke prediction system. The forecast was necessary to help anticipate fire and smoke behavior and to determine the most effective observational configuration. Onsite meteorological information was used to validate and improve the weather components of BlueSky and PB-Coastal Plain. A standard configuration of BlueSky was run to help with preburn forecasting and 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. The meteorological observations included four surface weather stations at strategic points around the fire perimeter to capture surface drift smoke and influencing weather. Each station measured wind, temperature, humidity, and carbon monoxide every 5 minutes. Additional stations—Data-logging Real-time Aerosol Monitors (DataRAM) and Environmental Beta-Attenuation Mass Monitor (E-BAM)—outfitted with a $PM_{2.5}$ sampler were placed in expected downwind locations away from the fire perimeter to capture outflow rates. The location of each sampling station was based on the topographic configuration of the area, expected weather, and anticipated fire and smoke behavior. The meteorological data were monitored during each experiment to ensure quality control. This sampling methodology has been successfully deployed at the FROSTFIRE experimental burn in Alaska (Ferguson and others 2003) and the surface measurements have been tested during experimental burns in Washington, Oregon, and the Piedmont region of northern Georgia with success. Before each experiment a standard configuration of the BlueSky smoke modeling system was run that used the CALPUFF dispersion model. The system was rerun following each experiment in an enhanced mode that adjusts available preburn 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.

Results and Discussion

Vegetation Classification and Current Forest Biomass

Six research prescribed burns were monitored during the first 2 years of the study. The following preliminary information characterizes two research burns conducted on March 3 (day 1) and 4 (day 2), 2006 at the Alligator River National Wildlife Refuge and the Air Force Dare County Bombing Range in North Carolina (fig. 1 and 2). Seven vegetation alliances were identified on the research site (table 1). The Pond Pine Saturated Woodland Alliance was delineated as woodland and overstocked woodland for establishment of field plots but were combined for the fuel loading analysis. The Shining Fetterbush-Little Gallberry Shrubland and the Sweetbay-Swampbay Saturated Forest Alliances did not meet the minimum mapping unit size and were not included in the fuel loading analysis.

Preliminary trends in pre- and postburn biomass for North Navy Shell prescribed burns day 1 and day 2 are shown in tables 2 and 3. Fuels were characterized in 12 ft diameter microplots into live and dead herbaceous

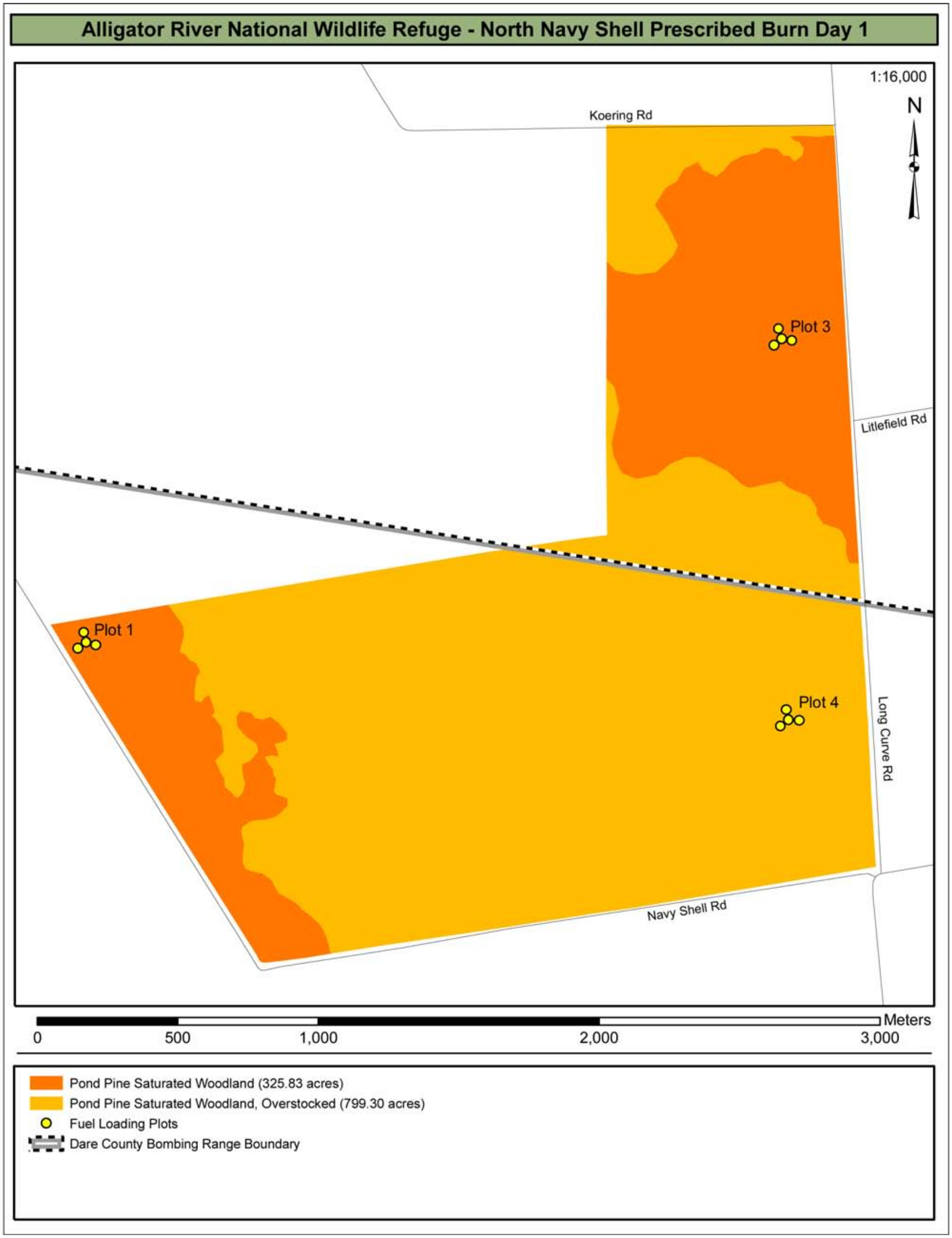

Figure 1—Delineation of vegetation alliances and acres for prescribed burn day 1.

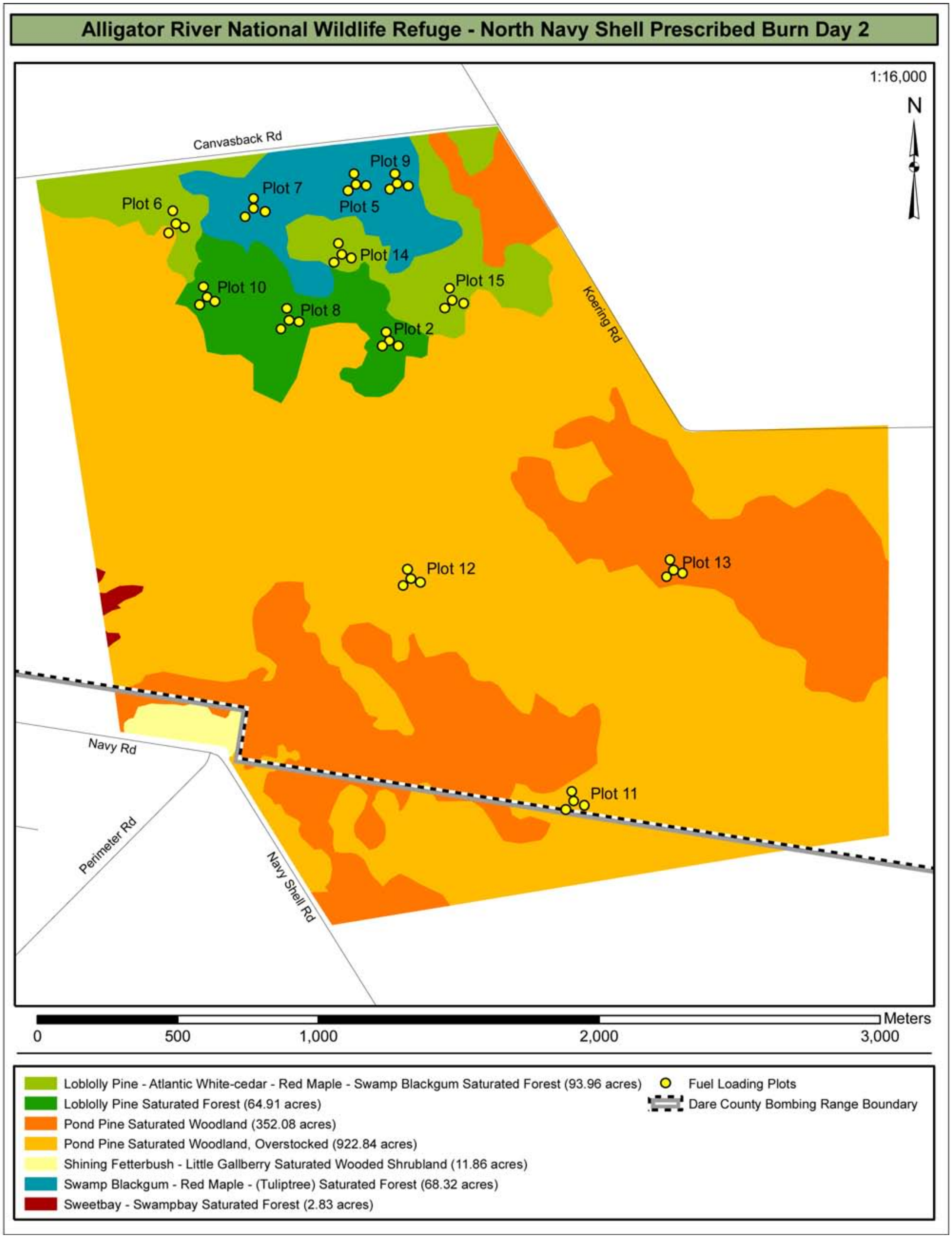

Figure 2—Delineation of vegetation alliances and acres for prescribed burn day 2.

Table 1—Summary of North Navy Shell prescribed burns day 1 and day 2 forest type acres.

Rx burn	Forest type	Acres	Pct.
North Navy Shell day 1	Pond pine saturated woodland	325.83	28.96
	Pond pine saturated woodland, overstocked	799.30	71.04
	Total	**1,125.13**	**100**
North Navy Shell day 1	Loblolly pine-AWC-maple-blackgum forest	93.96	6.19
	Loblolly pine saturated forest	64.91	4.28
	Pond pine saturated woodland	352.08	23.21
	Pond pine saturated woodland, overstocked	922.84	60.84
	Swamp blackgum-swampbay saturated forest	68.32	4.50
	Shining fetterbush-little gallberry shrubland	11.86	0.08
	Sweetbay-swampbay saturated forest	2.83	0.02
	Total	**1516.80**	**100**

Table 2—Summary of biomass for 1,125.33 acres day 1 prescribed burn (March 3, 2006) on the Alligator River National Wildlife Refuge and the Air Force Dare County Bombing Range, NC.

Vegetation alliance		**Duff (Oa)**					**Litter 1 hr fuels**	**Fine woody 1 hr fuels**	**Fine woody 10 hr fuels**	**Fine woody 100 hr fuels**	**Coarse woody 1000 hr fuel**	**Total litter and woody fuels**
			Dead shrub	**Live shrub**	**Dead herb**	**Live herb**	**Litter**	**(0-0.25 in)**	**(0.25-1.0 in)**	**(1-3 in)**	**(>3 in)**	
	Preburn											
Pond pine woodland	tons/acre	334.1	0.36	1.66	0.00	0.03	9.97	0.41	1.41	1.81	1.19	14.79
	total tons	375,972.75	405.12	1,868.05	0.00	33.76	11,219.54	461.39	1,586.72	2,036.85	1,339.14	16,643.63
	Postburn											
Pond pine woodland	tons /acre	334.1	0.36	1.66	0.00	0.03	6.30	0.11	1.22	1.81	1.19	10.63
	total tons	375,972.75	405.12	1,868.05	0.00	33.76	7,089.58	123.79	1,372.90	2,036.85	1,339.14	11,962.26
	Consumed											
Pond pine woodland	tons/acre	0.00	0.00	0.00	0.00	0.00	3.67	0.39	0.30	0.00	0.00	4.36
	total tons	0.00	0.00	0.00	0.00	0.00	4,129.96	337.60	213.81	0.00	0.00	4,681.37

Table 3—Summary of biomass for 1,516.8 acres day 2 prescribed burn on the Alligator River National Wildlife Refuge and Air Force Dare County Bombing Range, NC.

Vegetation alliance		Plot	Duff (Oa)					Litter 1 hr fuels	Fine woody 1 hr fuels	Fine woody 10 hr fuels	Fine woody 100 hr fuels	Coarse woody 1000 hr fuels	Total litter and woody fuels
				Dead shrub	Live shrub	Dead herb	Live herb	Litter	(0-0.25 in)	(0.25-1.0 in)	(1-3 in)	(>3 in)	
Loblolly pine forest	Preburn												
64.91 acres	tons/acre		299.95	0.53	2.22	0.00	0.00	7.70	0.27	1.95	2.20	2.59	14.71
	total tons		454,918.66	803.90	3,367.30	0.00	0.00	11,679.36	409.54	2,957.76	3,336.96	3,928.51	22,312.13
	Postburn												
	tons/acre		299.95	0.50	2.14	0.00	0.00	3.93	0.12	1.49	1.62	2.59	25.12
	total tons		454,918.66	758.40	3,245.95	0.00	0.00	5,961.02	182.02	2,260.03	2,457.22	3,928.51	14,813.92
	Consumed												
	tons/acre		0.00	0.03	0.08	0.00	0.00	3.77	0.15	0.46	0.69	0.00	5.07
	total tons		0.00	45.50	121.35	0.00	0.00	5,718.34	227.52	697.73	879.74	0.00	7,523.33
Pond pine woodland	Preburn												
1,274.92 acres	tons/acre		405.19	0.81	1.02	0.00	0.00	7.23	0.34	1.82	1.80	1.10	12.29
	total tons		614,592.19	1,228.61	1,547.14	0.00	0.00	10,966.46	515.71	2,760.58	2,730.24	1,668.48	18,641.47
	Postburn												
	tons/acre		405.19	0.64	0.99	0.00	0.00	1.38	0.07	1.17	1.66	1.10	5.38
	total tons		614,592.19	970.75	1,501.63	0.00	0.00	2,093.18	106.18	1,774.66	2,517.89	1,668.48	8,160.39
	Consumed												
	tons/acre		0.00	0.17	0.03	0.00	0.00	5.85	0.27	0.65	0.14	0.00	6.91
	total tons		0.00	257.86	45.51	0.00	0.00	8,873.28	409.54	985.92	212.35	0.00	10,481.09
Loblolly pine-AWC-maple-blackgum forest	Preburn												
93.96 acres	tons/acre		226.28	0.53	1.98	0.00	0.00	4.94	0.48	2.10	2.13	17.66	27.31
	total tons		343,221.50	803.90	3,003.26	0.00	0.00	7,492.99	728.06	3,185.28	3,230.78	26,786.68	41,423.79
	Postburn												
	tons/acre		226.28	0.53	1.98	0.00	0.00	4.30	0.48	2.10	2.13	17.66	26.67
	total tons		343,221.50	803.90	3,003.26	0.00	0.00	6,522.24	728.06	3,185.28	3,230.78	26,786.68	40,453.04
	Consumed												
	tons/acre		0.00	0.00	0.00	0.00	0.00	0.641	0.00	0.00	0.00	0.00	0.64
	total tons		0.00	0.00	0.00	0.00	0.00	970.75	0.00	0.00	0.00	0.00	970.75
Blackgum-maple forest	Preburn												
68.32 acres	tons/acre		226.28	0.36	1.05	0.00	0.01	1.83	0.33	1.14	1.67	6.21	11.18
	total tons		343,221.5	546.05	1,592.64	0.00	15.17	2,775.74	500.54	1,729.15	2,533.06	9,419.33	16,957.82
	Postburn												
	tons/acre		226.28	0.32	1.00	0.00	0.01	1.83	0.33	1.14	1.67	6.21	11.18
	total tons		343,221.5	485.38	1516.80	0.00	15.17	2,775.74	500.54	1,729.15	2,533.06	9,419.33	16,957.82
	Consumed												
	tons/acre		0.00	0.04	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	total tons		0.00	60.67	75.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

plant biomass, and live and dead shrub biomass. Litter, 1-, 10-, 100-, and 1,000-hour fuels were estimated from line intersects. The large source of carbon emissions was found in the litter layer, followed by 1-hour DWD, 10-hour DWD, and 100-hour fuels.

Emission Factors

The emission factors (EFs) resulting from the samples collected during each phase of the prescribed burn are presented in table 4. $PM_{2.5}$ typically composes at least two-thirds of total PM, and roughly 80 percent of PM_{10} from biomass combustion sources (Andreae and Merlet 2002). Our data are consistent with these relative proportions. The $PM_{2.5}$ and PM_{10} EFs determined using the Met One sensor are lower than the filter based methods, likely because this instrument has a 0.5 µm lower diameter detection limit. A large fraction of biomass burning particles falls below this size cut (Hays and others 2002). CO_2 emission factors are important because they represent the largest carbon component of emissions. The integrated concentration values from the continuous CO_2 emission monitor exceeded or were nearly equal to the concentration determined from the Summa canister during the flaming stages of the fires. It is not known if possible reactions within the canister might affect this comparison. In any case, this method-induced variability in CO_2 concentrations induced an uncertainty in emission factors of all gasses and particles of 0 to 10 percent.

In general, the $PM_{2.5}$ and PM_{10} EFs are lower those published in other open biomass burning studies. Observed NOx EFs are also lower, while those for SO_2 and total NMHC fall within the ranges of previously reported biomass burning studies.

For all of the prescribed fires, emission factors for CO_2 are higher than reported ranges (Andreae and Merlet 2002). 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,

Table 4—Emission factors derived from smoke samples of the North Navy Shell prescribed burn day 1 (emission factors in g kg (fuel dry weight)$^{-1}$).

Stage*	Time	PM_{10}	PM_{10M}	$PM_{2.5}$	$PM_{2.5Q}$	$PM_{2.5M}$	CO	CO_2	CO_{2c}	NO_X	THC	SO_2
Fl	11:41-13:02	6.49	2.92	6.49	4.87	2.22	44.18	1730	1700	2.07	10.1	0.55
Sm	13:47-16:30	3.38	1.67	2.07	2.41	0.84	34.09	950	920	0.81	303	0.43

Stage* Fl=Flaming stage, Sm=smoldering stage
PM_{10} determined gravimetrically from Teflon filter in single stage impactor.
PM_{10M} determined from Met One detector, measures PM 0.5 to 10 m.
$PM_{2.5}$ determined gravimetrically from Teflon filter in single stage impactor.
$PM_{2.5Q}$ determined gravimetrically from Quartz filter in single stage impactor.
$PM_{2.5M}$ determined from Met One detector, measures PM 0.5 to 2.5 m.
CO determined using TECO 46C continuous emission monitor.
CO_2 determined using GC/TCD analysis on Summa can samples.
CO_{2c} determined using TECO continuous emission monitor.
NO_X determined using TECO 42S continuous emission monitor.
THC determined using TECO continuous emission monitor.
SO_2 determined using TECO continuous emission monitor.

which minimizes consumption of soil organic layers and smoldering of heavy fuels. Combustion of these fuel components often results in higher emission of products of incomplete combustion.

Smoke Trajectory and Concentrations

The BlueSky modeling framework output products include animations of $PM_{2.5}$ concentrations and wind flow patterns at the surface. An example of an hourly image from the animation is shown in figure 3. Fire characteristics are processed through the Emissions Production Model (EPM) to give emission estimates of particulates ($PM_{2.5}$, PM_{10}, and total PM), carbon compounds (CO, CO_2, CH_4, nonmethane hydrocarbons), and heat. The emission estimates from EPM along with meteorology from the fifth generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5) are processed for the CALPUFF dispersion model and the HYSPLIT trajectory model. The BlueSky framework merges meteorology with emission estimates to yield an integrated regional-scale analysis of smoke and aerosol concentrations.

Primary inputs to BlueSky include weather, fire characteristics, and fuels. Predictions of wind speed and direction as well as mixing height are required to determine smoke trajectories and $PM_{2.5}$ concentrations. Weather inputs come from the MM5 mesoscale meteorological model. In order to arrive at an accurate prediction of smoke emissions it is necessary to get detailed information about size, location, and timing of the prescribed burn. Fuel model and fuel loading information is essential to emissions modeling. BlueSky uses general fuel characteristics derived from one of several fuel model systems, including the Fuel Characteristic Classification System (FCCS), but for this

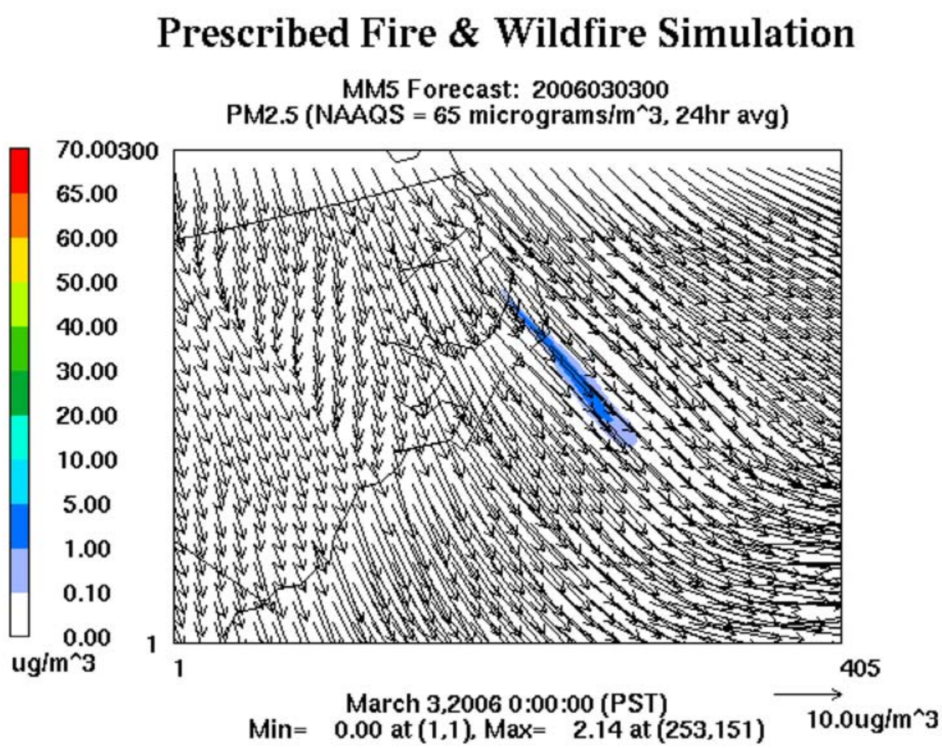

Figure 3—Prescribed fire simulation from BlueSky for North Navy Shell prescribed fire research burn. $PM_{2.5}$ ground concentrations (μg/m^3) and wind flow patterns are shown as houly image. MM5 meterology simulation was done on a 1.33 km resolution.

project detailed pre- and postburn fuel characteristics were collected from permanent field plots. Emissions are computed using Consume/EPM v1.03, which calculates the heat release rate and emissions for particulate matter and carbon compounds as a function of time since fire ignition. These emission values are input data for CALFUFF v5.711 that calculates the dispersion and plume rise. Trajectories are computed using the HYSPLIT model. HYSPLIT uses a full three-dimensional wind field for computational purposes but does not include any heat or buoyancy effects from fire.

The trajectory of the BlueSky smoke plume correlates well with a NOAA GOES satellite image of the smoke plume (fig. 4). The Hazard Mapping System Fire and Smoke Product image is derived from an interactive processing system that allows the trained satellite analysts in the Satellite Analysis Branch (SAB), within the Satellite Services Division (SSD), to manually integrate data from various automated fire detection algorithms with GOES and polar (Advanced Very High Resolution Radiometer; AVHRR), Moderate Resolution Imaging Spectroradiometer Fire Algorithm (MODIS), and Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) images. The result is a quality controlled display of the locations of fires and significant smoke plumes detected by meteorological satellites. Prior to ignition of the prescribed burn, VSMOKE, a computer program for predicting the smoke and dry weather visibility impact of a single prescribed

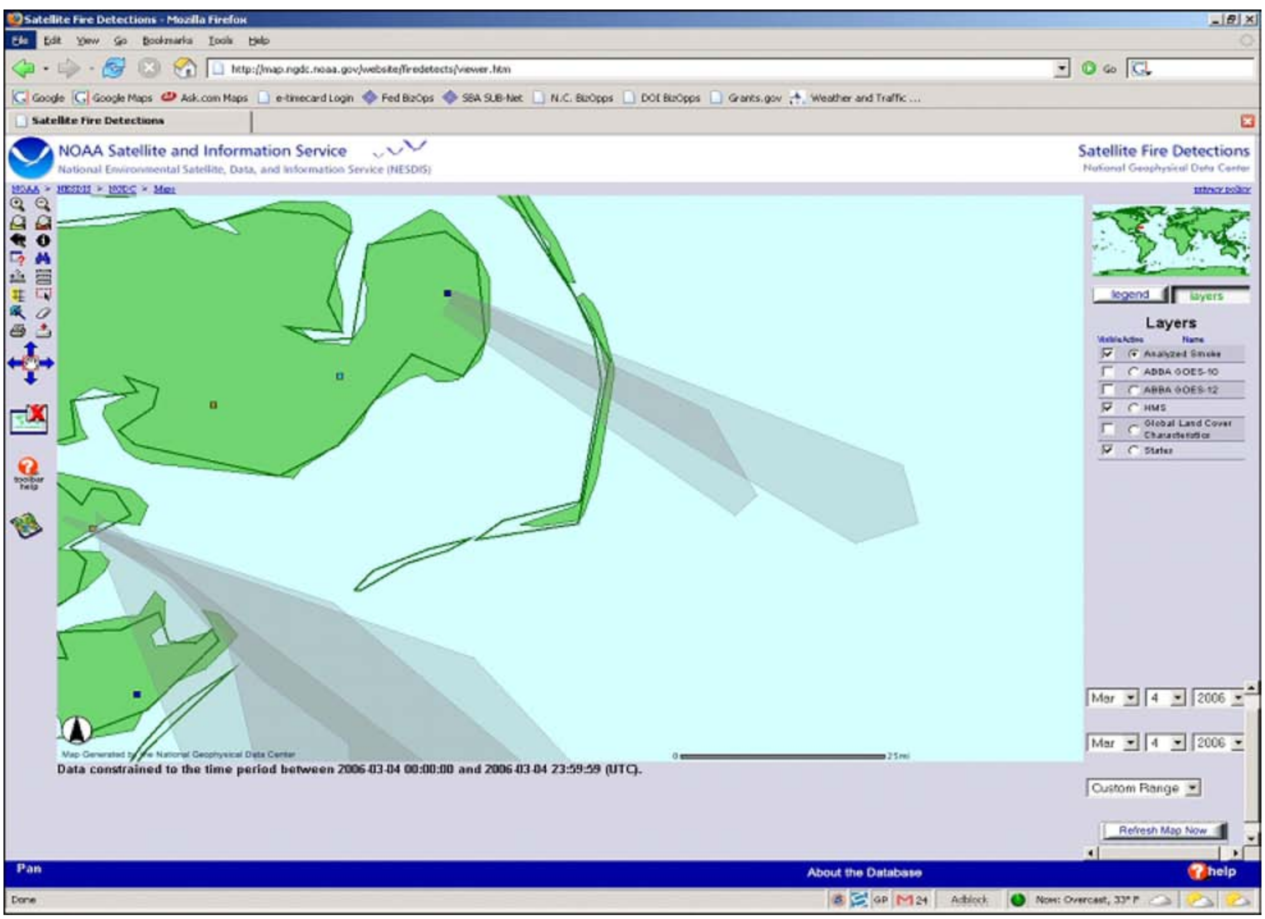

Figure 4—Hazard Mapping System Fire and Smoke Product image derived from various automated fire detection algorithms with GOES and polar Advanced Very High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer Fire Algorithm (MODIS) and Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) images.

fire at several downwind locations, was run for current weather conditions. Figure 5 illustrates the smoke plume trajectory and visibility impacts. The BlueSky modeled plume trajectory and $PM_{2.5}$ concentrations may result in an accuracy improvement when compared to V-SMOKE predictions. Accurate representation of the wind field and other meteorology parameters within the BlueSky modeling framework may further our understanding of fire behavior and its relationship to smoke management on deep organic soils.

Summary and Conclusions

Land managers in the Coastal Plain of the Eastern United States recognize general fuel types on organic soils and mineral soils. Past fuel and fire behavior research has resulted in only qualitative measures of fuel loads and rates of spread. A more detailed fuel classification based on species composition, standing dead and down deadwood, fuel size classification, understory vegetation, and vertical distribution of fuels would have much more utility than the broad fuel model classification system now in use. Fire in the organic and mineral soil areas of the Coastal Plain centers around the frequent and costly blowup wildfires occurring there and the use of fire as a fuel reduction and habitat management tool. Wildfires in this area can, under certain combinations of fuel and weather, grow from a low intensity burn to a virtually uncontrollable burn until weather conditions change or the fire has run out of fuel. 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. A better understanding of the behavior of fires and the role of fuel loading in fire behavior in the pocosins, especially the factors that contribute to the occurrence of major fires, will contribute to the control of wildfires and the use of prescribed fire as a management tool in the region.

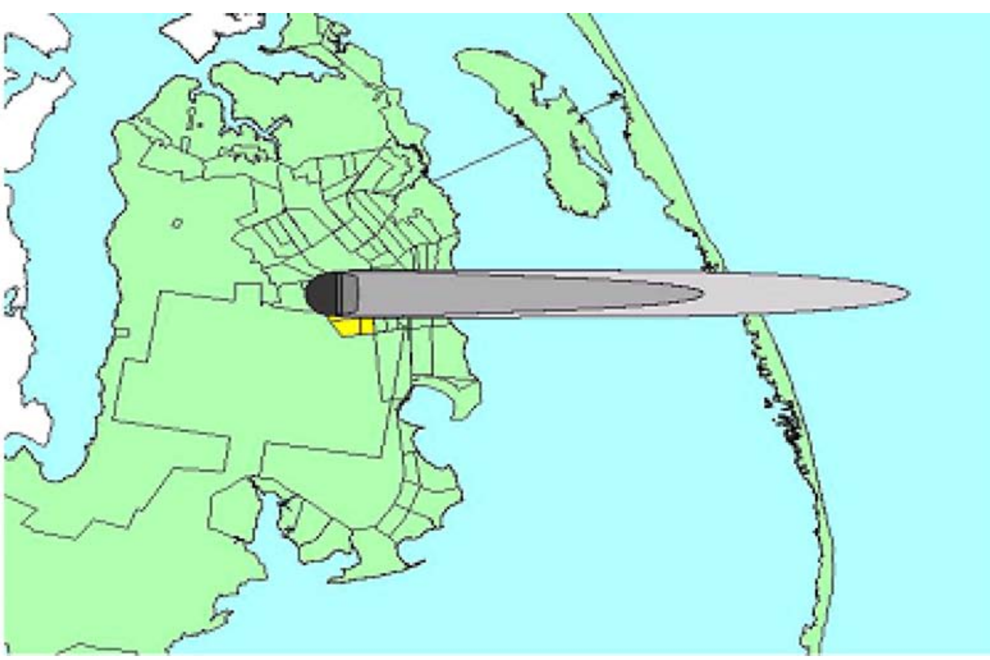

Figure 5—VSMOKE prediction of smoke and dry weather visibility impacts.

The methodology of using modified National Vegetation Classification Alliance level vegetation maps, created from digital photogrammetry and FIA P3 data, shows promise as an approach to fuel mapping. Softcopy photogrammetry, coupled with ground truthing, provides a high level of accuracy for mapping to the association level of the ICEC system. Fuel loads generated from the FIA P3 plots differ from fuel loads estimated using the standard fuel models. These differences could have an impact on the prediction of fire spread and behavior. Fuel loads within fuel size classes did vary between the modified association level classifications. Disturbance history appears to play a significant role in explaining why fuel loads differ and could help in creating more accurate fuel maps. Research of this nature may lead to use of FIA P3 plot data to generate an index of fuel load by ICEC association level vegetation classification. This could lead to a valuable multipurpose tool for land managers and researchers for use in predicting, preventing, and managing forest biomass for wildfire.

The U.S. 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, 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 g m^{-3}, annual mean, and 50 g m^{-3}, 24-hour average, to provide increased protection against a wide range of PM-related health effects. These include premature mortality and 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. Recent proposals would reduce the 24-hour average $PM_{2.5}$ standard to 35 g m^{-3}. Fire generates $PM_{2.5}$ and other 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 that contribute to NAAQS violations.

Little data on emissions from prescribed burning are currently available, and this fire type in particular is projected to increase in the Southeastern United States. We hypothesize 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 is dry and susceptible to smoldering and incomplete combustion, the source of many toxic compounds. It is likely that burning under prescriptions will reduce human exposure and emissions of hazardous air pollutants, and net risk to property and human welfare.

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Acknowledgments

Funding for this study was provided by the Joint Fire Science Program (Project 04-2-1-80). Additional support was provided by the U.S. Air Force Air Combat Command, Richard Lemaire, Dr. Terry Bashore, Bryan Henderson, Joe Lafferty, Scott Smith, and Harry Mann, U.S. Navy. The authors wish to acknowledge the U.S. Fish and Wildlife Service (USFWS) support of Mike Bryant, Kathy Whaley, Tom Crews, Vince Carver, Donnie Harris, Kelley Van Drueten, Greg Suszek, Pete Kubiac, Glen Stratton, the prescribed fire staffs on USFWS Fire District 1, and Gary Curcio and the North Carolina Division of Forest Resources.