Fuel consumption and particulate emissions during fires in the New Jersey Pinelands

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Abstract
We quantified loading and consumption losses of 1-hour and 10-hour fuels on the forest floor and understory vegetation during 24 operational prescribed burns conducted in the Pinelands National Reserve of New Jersey. PM 2.5 emissions were calculated using published emission factors, and atmospheric PM 2.5 was measured under ambient conditions and during prescribed fires. Pre-burn 1-h and 10-h fuel loading was greater in Pitch pine-dominated stands than in stands with a substantial biomass of overstory oak.

Forest floor and understory fuel consumption were a strong linear function of pre-burn loading, and forest floor consumption was often the predominate site of PM 2.5 production, even during crowning fires. These relationships allow a more accurate estimate of PM 2.5 production during fuel reduction treatments, based on knowledge of pre-burn fuel loading.

Additional keywords: Prescribed burning, , PM 2.5, Pinelands National Reserve, prescribed fire emissions, wildfire emissions, air quality, available fuel, fuel loading

Introduction

Prescribed fires are essential for the protection of homes and property from wildfires. Smoke from prescribed fires contributes to atmospheric pollutant loads, and where prescribed fires are conducted near urban centers or non-attainment areas, the potential exists for exceeding federal, state or local air quality standards (Tian *et al*. 2008). In addition, impairment of visibility by smoke on roads and highways can be a significant safety hazard.

The proximity of residential developments and commercial property to the nearly continuous fuel beds of the Pinelands National Reserve is a major concern for the New Jersey Forest Fire Service (NJFFS) and federal wildland fire managers. They have two major goals when using prescribed fire; to reduce fuels on the forest floor, and to reduce the occurrence of ladder fuels in the understory. Ladder fuels, consisting of shrubs and sub-canopy foliage and branches, increase vertical and horizontal fuel continuity, and can facilitate the transition of surface fires to the canopy, where they are much more difficult and expensive to suppress (e.g., Skowronski *et al*. 2007, Clark *et al*. 2009). In an effort to reduce the threat of crown fires impacting housing developments, commercial property and transportation corridors along the eastern margin of the Pinelands National Reserve, many prescribed burn blocks in the Pinelands have been burned at 5-8 year intervals since the late 1950's. A number of these burn blocks are aligned along a north-south axis, and along with wetlands and stream corridors, serve as landscape-scale fire breaks under the prevailing NW winds.

Although a planning framework exists to mitigate the direct effects of smoke on communities and highways during prescribed burn treatments within the NJFFS and federal wildland fire management agencies, information is limited regarding fuel consumption and production rates of particulate matter less than 2.5 µg in size (PM 2.5) during prescribed burns in Pineland plant communities. Little ambient air data for PM 2.5 in the Pinelands exists, despite the fact that this region has one of the highest incidences of wildfires in the Northeastern US, and is located adjacent to large urban and industrial areas. Emissions from prescribed burns or other fuel treatments have rarely been compared to those from wildfires, precluding an evaluation of the tradeoffs between various hazardous fuels management strategies (e.g., Tian *et al*. 2008). Because prescribed fires are currently the most cost-effective method of treating hazardous fuels, a strong need exists to prioritize and maximize the effectiveness of fuel reduction treatments given the new 24 hour PM 2.5 ambient air standard is now 35 µg of PM 2.5 m^{-3} (EPA 2007a-c). Further complicating the situation is the fact that two counties in and surrounding the Pinelands (Burlington and Camden) were non-attainment areas for PM 2.5 in 2010 (http://ecfr.gpoaccess.gov/cgi/).

Our objectives were to:

1) Quantify fuel loading and consumption during operational prescribed fires conducted by the NJFFS in the Pinelands National Reserve.

2) Calculate PM 2.5 emissions from prescribed fires, and compare them to estimated PM 2.5 emissions from the May 2007 Warren Grove wildfire.

3) Monitor ambient air concentrations of PM 2.5 in the Pine Barrens throughout 2008 to determine seasonal patterns and seasonal occurrence of non-attainment days.

4) Measure PM 2.5 concentrations near and in a series of prescribed fires conducted by the NJFFS near the Cedar Bridge fire tower in March 2008.

Methods

Site Description

Research sites were located in Burlington and Ocean Co. in the Pinelands National Reserve in southern New Jersey. The Pinelands contain the largest continuous forested landscape on the Northeastern coastal plain. The climate is cool temperate, with mean monthly temperatures of 0.3 and 23.8 ºC in January and June, respectively (1930-2009; State Climatologist of NJ; http://climate.rutgers.edu/stateclim_v1/data/). Mean annual precipitation is 1142 ± 160 mm. Soils are derived from the Cohansey and Kirkwood Formations, and are sandy, coarse-grained, and extremely oligotrophic (Tedrow 1986). This landscape is also characterized by a high frequency and intensity of wildfires relative to other forest ecosystems in the northeastern US (Little & Moore 1948, Little 1998).

Wildland fire managers in the Pinelands conduct prescribed burns on approximately 8,000 to 12,000 ha of public forest per year (Table 1). Upland forests are the major focus of fuel reduction treatments in the Pinelands. These comprise ca. 62% of the forested areas in the Pinelands

National Reserve, and are dominated by three major forest communities; 1) oak - pine, consisting of black oak (*Quercus velutina* Lam.), chestnut oak (*Q. prinus* L.), white oak (*Q. alba* L.), and pitch (*Pinus rigida* Mill.) and shortleaf pine (*P. echinata* Mill.), 2) pine - oak, consisting of pitch pine with mixed oaks in the overstory, and 3) pine - scrub oak, dominated by pitch pine with scrub oaks (*Q. ilicifolia* Wang. and *Q. marlandica* Muench.) in the understory (McCormick & Jones 1973, Lathrop & Kaplan 2004, Skowronski *et al*. 2007, FIA data at www.fia.gov). A fourth forest community, the pine plains, consisting of short-statured pitch pine and scrub oaks, is also recognized in the vicinity of Coyle Field, Warren Grove Bombing Range, and Stafford Forge Wildlife Management Area. All stands have ericaceous shrubs in the understory, primarily huckleberry (*Gaylussacia bacata* (Wang.) K. Koch, *G. frondosa* (L.) Torr. & A. Gray ex Torr.) and blueberry (*Vaccinium* spp.). Sedges, herbs, mosses and lichens also are present (Wright *et al*. 2007).

Table 1. Acreage of prescribed fires conducted by the NJFFS in the Pinelands National Reserve from 2002 to 2008. Acres burned are from NJFFS. The sampled area is the sum of stand acreage sampled for fuel loading each year, and % is the percent of total burned area sampled each year.

Year	Hectares	Sampled area	%
2002	4898	-	-
2003	3849	-	-
2004	3250	918	28
2005	4065	295	7
2006	3150	404	13
2007	4720	202	4
2008	7520	459	6

Most upland forest stands in the Pine Barrens have regenerated naturally following cessation of logging and charcoaling activities in the late 1800's. Among mature upland stands of approximately the same age, understory fuel loading and ' ladder fuels' are typically denser in pine - oak and pine – scrub oak stands compared to oak-dominated stands (Skowronski *et al*. 2007).

Fuel Loading and Consumption Measurements

Fine (1-h), 10-h and 100-h fuels were sampled on the forest floor in 30 stands throughout the Pinelands. Stands were located in the Brendan T. Byrne State Forest, Greenwood and Stafford Wildlife Management Areas, Fort Dix Army Base, and Wharton State Forest, and encompassed a wide range of tree densities and fuel loadings. Pre-burn forest floor measurements consisted of 10 to 20 1 m^2 quadrats located at random points within each treatment block. We sampled the litter layer (L horizon) only, because the humus layer (O horizon), consisting of undifferentiated organic matter, rarely was consumed during prescribed fires. In the laboratory, samples were separated into 1-h, 10-h and 100-h fuels. All samples were dried at 70 ºC until dry, and then weighed. Shrubs, herbs, and understory oaks < 2 m tall were sampled in addition to forest floor fuels at twelve of the stands. Understory vegetation was cut at ground level, and separated into foliage and live and dead 1-h, 10-h, and 100-h fuels in the laboratory. Samples were dried at 70 ºC until dry, and then weighed.

Of the thirty stands initially sampled, twenty-four were burned in prescribed fires. These stands were re-sampled for unconsumed 1-h, 10-h, and 100-h fuels within one week of burning, using the same protocols that were used for pre-burn samples. On the days of many of the prescribed burns, fuel moisture content of 1-h and 10-h fuels on the forest floor and in understory vegetation was estimated using wet and dry weight measurements of samples collected in plastic bags. Meteorological data, 10-h fuel moisture contents and temperatures, and other ancillary data were recorded for each burn from fire weather towers in the Pinelands (http://climate.rutgers.edu/usfs/ monitoring.pfp). We also sampled a pitch pine – scrub oak stand in the Stafford Wildlife Management Area that was burned in an intense crowning prescribed fire conducted on March 21, 2008 to estimate emissions from the 6,300 ha Warren Grove wildfire that occurred on May 15th-19th, 2007. In addition to forest floor and understory measurements, LIDAR data (described in Skowronski *et al*. 2007 and Clark *et al*. 2009) collected pre- and post-burn were used to calculate canopy fuel consumption.

PM 2.5 Emissions from Prescribed Fires

Emissions from fires were calculated as the product of the area of the burn, the fuel consumed per unit area, and an emission factor:

$$E = A \times F_{area} \times E_{factor} \quad (1)$$

where A is the area burned, F_{area} is the amount of fuel consumed per unit area during the fire, and E_{factor} is the ratio of the mass of pollutant emitted per unit mass of fuel consumed. F_{area} and E_{factor} are functions of fuel conditions (e.g., availability and moisture content) and meteorological conditions during the burn. We used prescribed burn plans prepared by the NJFFS and burn perimeter measurements to calculate the area burned (A). Differences between mean pre- and post-burn fuel loadings were used to calculate the consumption of fine (1-hour), 10-hour and 100-hour fuels at each site (F_{area}).

Emissions (E_{factor}) from wildland fires and prescribed burns are well-characterized, and an extensive set of emission factors exist for EPA criteria pollutants and many hazardous airborne chemicals released from combustion of hardwood and coniferous fuels. We used EPA's Factor Information Retrieval Data System, FIRE 6.25 available from WebFIRE (http://www.epa.gov/ttn/chief/ efpac/index.html) and other literature values (Battye and Battye 2002) to estimate emissions of PM 2.5, CO_2, CO, and NMHC during combustion of forest fuels (Table 2). Mean emission factors for both wildfires and prescribed burns were used to calculate emissions of PM 2.5 from the intense crowning prescribed fire conducted in the Stafford Forge WMA in 2008, and estimated emissions from this burn were used to predict emissions from the Warren Grove wildfire.

Table 2. Mean emissions of fine particulates (PM 2.5), carbon dioxide (CO_2), carbon monoxide (CO) and non-methane hydrocarbons (NMHC) during wildfires and prescribed burns used for all calculations. Data are summarized from WebFIRE (http://www.epa.gov/ttn/chief/ efpac/index.html).

Fire type	PM 2.5	CO_2	CO	NMHC
	kg emitted per ton fuel consumed (kg ton^{-1})			
Wildfires	6.2 ± 0.5	1637	57.8 ± 15.3	4.3 ± 3.6
Prescribed fires	12.3 ± 1.0	1627 ± 50	140.5 ± 49.9	4.7 ± 2.0

We used the annual acreage burned from 2002 to 2008 in Table 1, mean consumption rates estimated from pre- and post-burn measurements, and emission factors in Table 2 to calculate annual emissions from operational prescribed fires conducted on public lands in the Pinelands by the NJFFS. Annual estimates of emissions released during prescribed fires were then compared to estimated PM 2.5 emissions from the Warren Grove wildfire in 2007.

PM 2.5 Measurements

Continuous PM 2.5 measurements were made at an oak - pine stand at the Silas Little Experimental Forest at the western edge of the Pinelands, and at a pine - scrub oak stand near the Cedar Bridge fire weather tower towards the eastern edge of the Pinelands in 2008. Two E-BAM beta particle attenuators (Met One Instruments, Inc., Grants Pass, Oregon) were fit with PM 2.5 sharp cut cyclone inlets, and operated using the manufacturer's specifications. When collectors were operated concurrently at Silas Little Experimental Forest, PM 2.5 concentrations were nearly identical. Both instruments were then located near fire weather or eddy flux towers (Clark *et al.* 2010), and operated according to the US EPA guidelines, and those in the instrument manual. Hourly or 24-hour averages of $\mu g\ m^{-3}$ PM 2.5 were used for all calculations.

In March 2008, the collector located at the oak-pine stand was relocated to an open area near the Cedar Bridge fire weather tower to monitor PM 2.5 concentrations during a series of prescribed fires. During these burns, one E-BAM was located within the burn block near the flux tower, and the second instrument was located in an adjacent feed plot clearing that was not burned (Fig. 1).

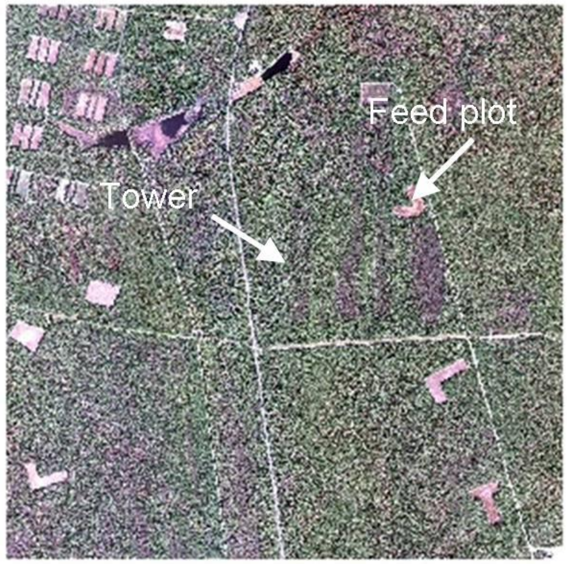

Fig. 1. Digital orthophoto of the Cedar Bridge area in Greenwood Wildlife Management Area following a series of prescribed fires conducted in March 2008. The tower and feed plot where the EBAM PM 2.5 instruments were located are indicated with arrows. Unburned crowns are green and areas of crown scorch appear dark grey and black. Area shown in the image is ca. 9 km^2.

Results

Fuel Loading and Consumption Measurements

Mean loading of 1-hour and 10-hour fuels on the forest floor was 12.8 ± 3.3 t ha^{-1} for the 30 prescribed burns blocks sampled from 2004-2009 (Table 3). Values ranged from 6.5 ± 2.1 t ha^{-1} in a fuel break that was burned at 2-3 year intervals (shown in the center of Fig. 1, running north to south between SR 539 and an unpaved road to the west) to 23.4 ± 5.8 t ha^{-1} in a pine-scrub oak stand that had not burned since a large wildfire in 1963. Differences in mean loading of 1-hour fuels but not 10-hour fuels were detected among forest types (ANOVAs, $F = 5.35$, $df = 29$, $p < 0.01$ for 1-hour fuels, and $F = 1.81$, $df = 29$, $p < 0.20$ for 10-hour fuels). Total fuel loading on the forest floor (1 hour + 10 hour fuels) was also significantly different among forest types (ANOVA, $F = 5.86$, $df = 29$, $p < 0.005$). Oak – pine and pine – oak stands had lower 1-hour and total fuel loading on the forest floor than pine – scrub oak and pine plains stands (t-tests, $t = 3.87$, $df = 24$, $p < 0.001$ for 1-hour fuels and $t = 3.14$, $df = 24$, $p < 0.005$ for total fuel loading).

Table 3. Summary of 1-hour and 10-hour fuel loading on the forest floor in 30 upland forest stands in the New Jersey Pinelands. Data are mean t ha^{-1} ± 1 SD of mean values calculated from 10 to 20 1-m^2 plots located at random points throughout each stand. Stand types with different superscripts are significantly different at P < 0.01 for 1-hour fuels and P < 0.005 for 1hr + 10 hr fuels.

Forest type	n	1-hour	10-hour	1-h + 10-h
Oak - pine	5	8.4 ± 1.7[a]	1.7 ± 0.7	10.1 ± 2.1[a]
Pine - oak	14	9.8 ± 2.0[a]	2.1 ± 0.8	11.9 ± 2.3[a]
Pine - scrub oak	7	12.3 ± 1.8[b]	3.8 ± 3.3	16.1 ± 4.1[b]
Pine plains	4	11.6 ± 1.6[b]	2.5 ± 1.5	14.2 ± 2.7[b]

Mean live shrub and understory oak biomass in the twelve stands sampled was 5.4 ± 3.0 t ha^{-1}. Dead shrub and understory oak stems averaged 2.1 ± 2.4 t ha^{-1} across all stands sampled. The maximum live + dead understory loading was 11.7 ± 4.0 t ha^{-1} in a pine – scrub oak stand that had not burned since 1962.

Fuel loading and consumption during prescribed burns

For the 24 prescribed burns sampled for pre- and post-fuel loading from 2004-2009, mean initial loading for 1-hour and 10-hour fuels on the forest floor was 12.4 ± 2.7 tons ha^{-2}. Mean post-burn loading of 1-hour and 10-hour fuels on the forest floor was 6.6 ± 1.5 t ha^{-1}, and estimated consumption during prescribed fires averaged 5.8 ± 2.9 t ha^{-1}. Mean consumption of 1-hour fuels represented 47.3 ± 15.5 % of pre-burn loading, while mean consumption of 10-hour fuels was only 24.9 % of pre-burn loading. Actual consumption of 10-hour fuels on the forest floor was likely greater, because some shrub stems likely fell to the forest floor during and immediately following prescribed burn treatments but were not consumed. For the subset of prescribed fires where shrub combustion was estimated, total pre-burn loading of live + dead shrubs was 7.5 ± 3.8 t ha^{-1} and post-burn loading was 3.3 ± 2.0 t ha^{-1}.

Consumption of fuels on the forest floor during prescribed fires was a strong linear function of initial fuel loading, which explained ca. 74% of the variability in consumption of 1-hour fuels, and ca. 72% of the variability in consumption of 1-hour + 10-hour fuels (Table 4, Fig. 2). Consumption of live + dead shrubs was also a significant linear function of initial fuel loading (Table 4). Because fuel consumption was a function of initial fuel loading, Pitch pine-dominated stands had greater consumption losses than stands with a significant biomass of overstory oaks (10.2 ± 2.7 ton ha^{-1} vs. 3.7 ± 1.3 tons ha^{-1} consumed; $t = 4.006$, $df = 21$, $P < 0.001$).

Table 4. Summary of equations for the relationship between pre-burn fuel loading and consumption estimated from post-burn measurements for 1-hour and 10-hour fuels on the forest floor, and woody stems of shrubs and scrub oaks in the understory. Units are mean tons ha^{-1}, and data were fit to linear equations with the form: Consumption = a (fuel loading) - b.

Fuel type	a	b	r^2	P
1-hour	0.839	3.508	0.736	<0.001
1-h + 10-h	0.898	5.317	0.722	<0.001
Understory stems	0.673	0.866	0.687	<0.01

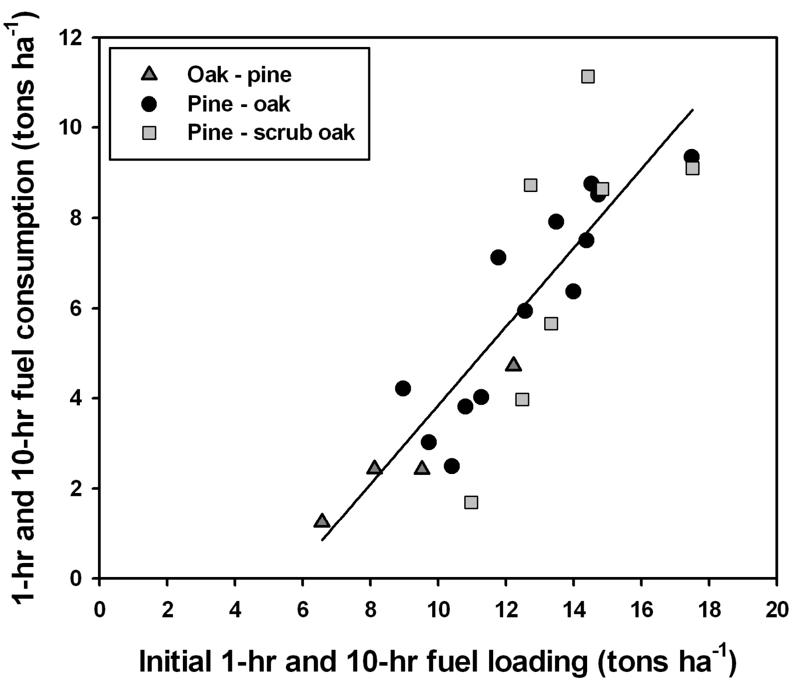

Fig. 2. The relationship between initial 1-h + 10-h fuel loading and amount of fuel consumed by forest type during 24 prescribed fires conducted in the Pinelands National Reserve in 2004-2009. Prescribed fires conducted in the Pine plains were included in the pine – scrub oak category. Statistics for the regression line are in Table 3.

Mean fuel consumption during prescribed fires was much less than that estimated for the large crowning prescribed fire conducted in March 2008 near the site of the Warren Grove wildfire (Table 4). Consumption of forest floor and understory stems during this crown fire was estimated at 16.1 t ha^{-1}, and total consumption was 18.6 t ha^{-1}. Although this was a high intensity crowning fire, the majority of consumption loss was due to combustion of forest floor and understory fuels (ca. 87% of total consumption).

Table 4. Pre- and post-wildfire fuel loading in the canopy, understory and forest floor, and estimated consumption during an intense crown fire conducted on March 21, 2008, near the site of the Warren Grove wildfire. Measurements were made in 1 m^2 plots in high intensity burn areas. All units are tons biomass or mass ha^{-1} ± 1 SD. The amount of total consumption accounted for by the overstory, understory, and forest floor is shown as a percent of total consumption %).

Component		Pre-fire	Post-fire	Consumption	%
Overstory[1]	Foliage	3.0	0.5	2.5	13 %
Understory:	Foliage	0.4 ± 0.5	0.4		39 %
	Stems	11.1 ± 6.2	4.3 ± 3.5	6.8	
Forest Floor:	1-hour	12.7 ± 1.6	5.0 ± 1.1	7.7	48 %
	10-hour	2.2 ± 1.1	1.2 ± 0.6	1.0	
	100-hour	0.8 ± 1.1	0.5 ± 0.9	0.2	
Total		30.2 ± 7.9	11.6 ± 3.2	18.6	

[1]Foliage and twig biomass in the canopy as calculated from LiDAR canopy bulk density measurements (Skowronski *et al*. 2010).

PM 2.5 emissions from prescribed burns
The mean value for PM 2.5 emissions during all prescribed burns sampled was 111 ± 46 kg PM 2.5 ha^{-1}. Estimated mean CO_2, CO and NMHC emissions averaged 14,711 ± 6,036, 1,270 ± 521, and 42 ± 17 kg ha^{-1} for all prescribed burns sampled, respectively. When analyzed by forest type, PM 2.5 emissions from a fuel break that was burned at 2-3 year intervals was least, and emissions from pine-oak and pine-scrub oak stands were greatest (Fig. 3). PM 2.5 emissions from the forest floor during the subset of crowning fires in pine-dominated stands averaged 102 ± 20 kg PM 2.5 ha^{-1}, compared to 55 ± 30 kg PM 2.5 ha^{-1} for prescribed burns that did not crown significantly. Values for CO_2, CO and NMHC emissions from the forest floor during crowning fires were estimated at 14,828 ± 2,688, 1,280 ± 232, and 43 ± 8 kg ha^{-1}, respectively.

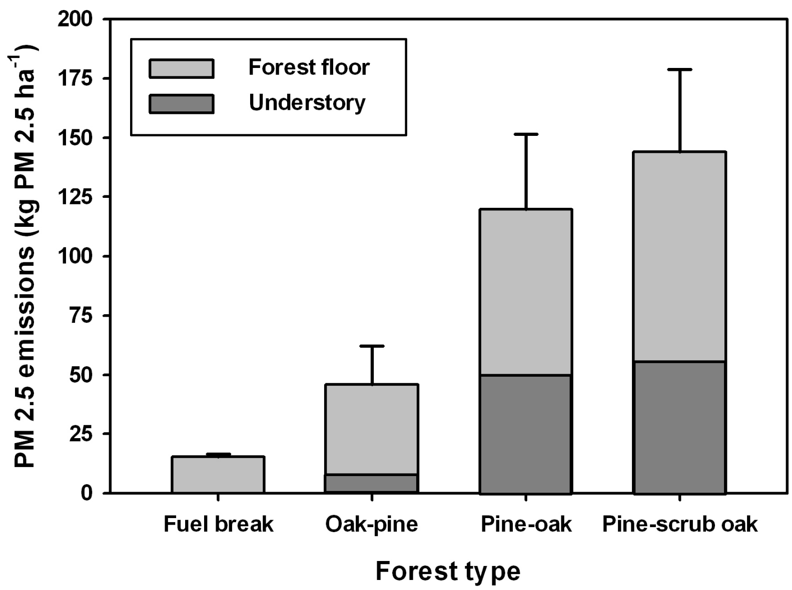

Fig. 3. Mean estimated PM 2.5 emissions during prescribed fires by forest type. Emissions are shown for 1-h and 10-h fuels on the forest floor, and understory vegetation separately.

PM 2.5 emissions from the Warren Grove wildfire were estimated at 115 ± 32 kg PM 2.5 ha^{-1} using the mean emission factor for wildfires listed in Table 1. If we assumed that half of the Warren Grove fire was characterized by smoldering fire due to protective backfire burning, then PM 2.5 emissions increased to 172 ± 46 kg PM 2.5 ha^{-1}.

For 2002-2008, estimated mean annual emissions of PM 2.5 from prescribed burns conducted on public lands by the NJFFS totaled 365 ± 121 tons PM 2.5 yr^{-1}. When variability in loading and annual area treated were considered, low and high estimates were 256 ± 95 and 611 ± 228 tons PM 2.5 yr^{-1} (Fig. 4). Total emissions from the Warren Grove wildfire in 2007, estimated from consumption data in Table 4 for the intense crowing fire that was conducted in 2008, was 727 ± 195 tons PM 2.5. Using mean emission factors for wildfires and prescribed fires together, total emissions from this wildfire were estimated at 1,084 ± 292 tons PM 2.5 (Fig. 4). These two mean estimates of PM 2.5 emissions from the Warren Grove wildfire exceed the average annual emission values calculated for prescribed fires by 2.0 and 3.0 times, respectively.

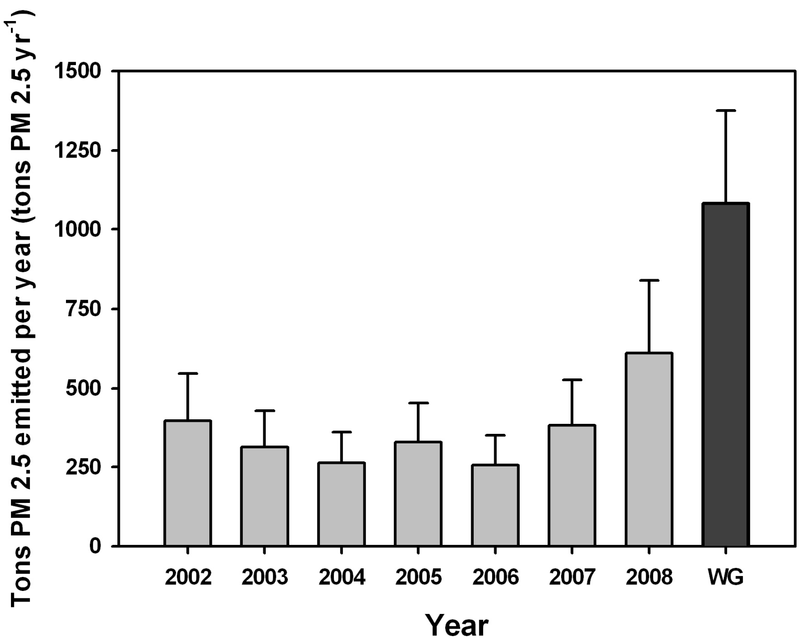

Fig. 4. Estimated annual PM 2.5 emissions for prescribed fires conducted on public lands by the New Jersey Forest Fire Service for 2002-2008. Estimated emissions from the Warren Grove wildfire (WG) on May 15-19th, 2007, are shown for comparison.

PM 2.5 in ambient air and during prescribed fires

Hourly PM 2.5 concentrations were generally less than the current EPA 24-hour standard of 35 µg m^{-3} during hourly measurements made in 2008 (Fig. 5). Three peaks in PM 2.5 concentrations occurred in 2008. The first peak was associated with the prescribed burns conducted near the Cedar Bridge fire tower during the end of March 2008, when we had the instruments near and in prescribed burns (data off-scale in Fig. 5). The second broad peak was associated with increased summer particulates in June-September, 2008, and the third peak in early October corresponds to wildfires in and near Wharton State Forest, when slightly enhanced PM 2.5 concentrations were detected at Silas Little Experimental Forest when prevailing winds were from the southwest. Seasonal mean hourly PM 2.5 concentrations reflected these patterns, with PM 2.5 concentrations averaging 4.40 ± 4.97 µg PM 2.5 m^{-3} from January through May (excluding data from the prescribed fires at Cedar Bridge), 8.53 ± 8.01 µg PM 2.5 m^{-3} during June through August, and 4.89 ± 8.01 µg PM 2.5 m^{-3} during September through December.

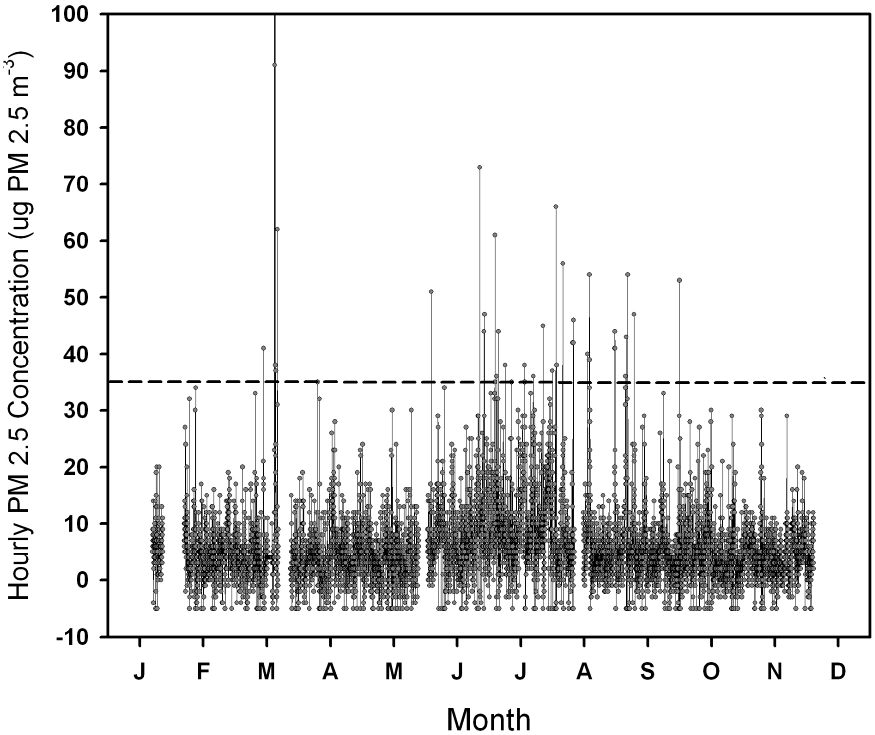

Fig. 5. Hourly PM 2.5 particle concentrations during January – December 2008 in the Pine Barrens. Data are pooled from collectors at the Silas Little Experimental Forest and near the Cedar Bridge fire tower. The dashed line indicates the current EPA PM 2.5 standard for a 24-hour period.

Closer detail of 24 hour PM 2.5 concentrations measured during the prescribed burning season (January through April) indicates that other than during the direct effects of prescribed fires, fine particulate concentrations were below the current EPA standard of 35 µg PM 2.5 in 2008 (Fig. 6).

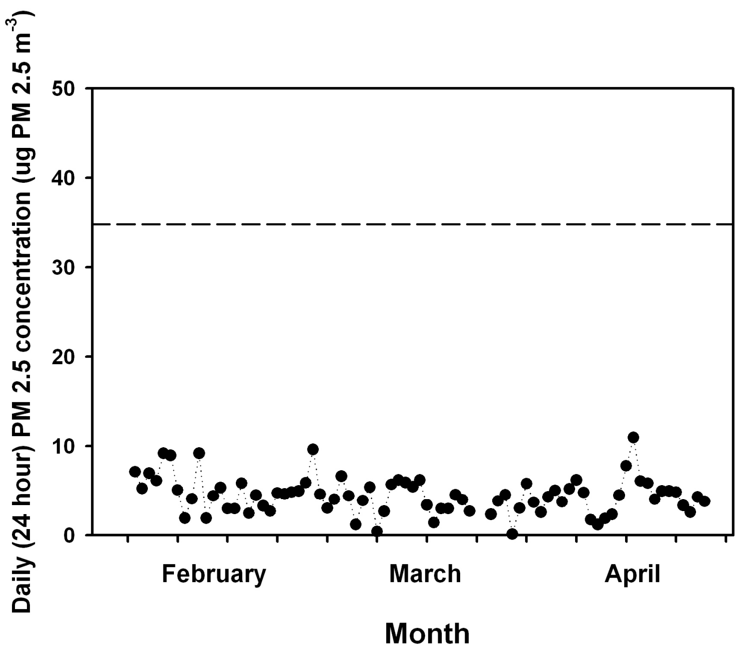

Fig. 6. 24-hour PM 2.5 concentrations for end of January through April 2008 at the Silas Little Experimental Forest, New Lisbon, NJ. The dashed line indicates the current EPA PM 2.5 standard for a 24-hour period.

Highest PM 2.5 concentrations in ambient air were measured during the end of March 2008, when both collectors were located near the Cedar Bridge fire weather tower during prescribed burning operations. A total of 1575 ha were burned in the Greenwood Wildlife Management Area during mid-March 2008, including the monitored stand on March 22, 2008 (Figs. 1, 7 and 8).

During the prescribed burn in the monitored stand on March 22, firing patterns differed between the tower and the feed plot measurement sites, with the burn initiated near the SE end of the feed plot at ca. 10:00 (Fig. 1). At ca. 12:00, the area near the main flux tower was fired. Hourly concentrations peaked at 4155 µg m^{-3} when the flame front and smoldering fire was burning within 1 m of the instrument, and then decreased exponentially (Figs. 7 and 8). At ca. 15:00 PM, the large block to the north and east of the feed plot was ignited. Hourly PM 2.5 concentrations at the feed plot instrument peaked at 873 µg m^{-3}, coincident with the time that this large block was fired (Fig. 1). By 18:00, a backing fire approached the flux tower from the east. Burning operations continued on the western edge of the block, along SR 539, until well after sunset. Overall, hourly concentrations peaked when flame fronts and smoldering fire were burning close to the instruments, and then decreased exponentially to below ambient air standards within 11 hours (Figs. 7 and 8).

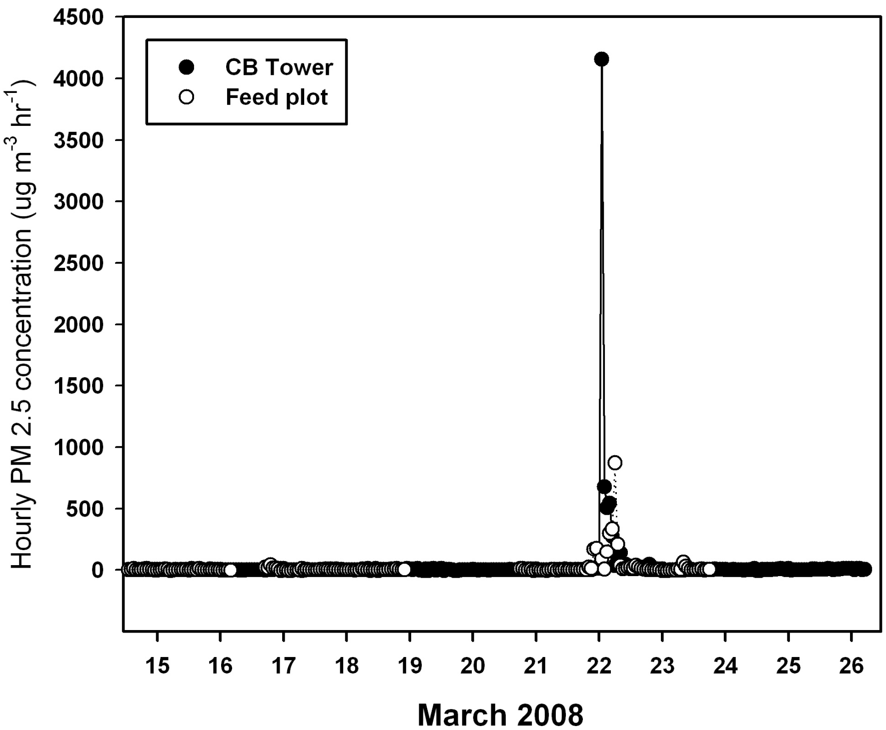

Fig. 7. Hourly PM 2.5 concentrations at the Cedar Bridge flux tower (●) and the adjacent feed plot (○) from March 15th to 26th, 2008.

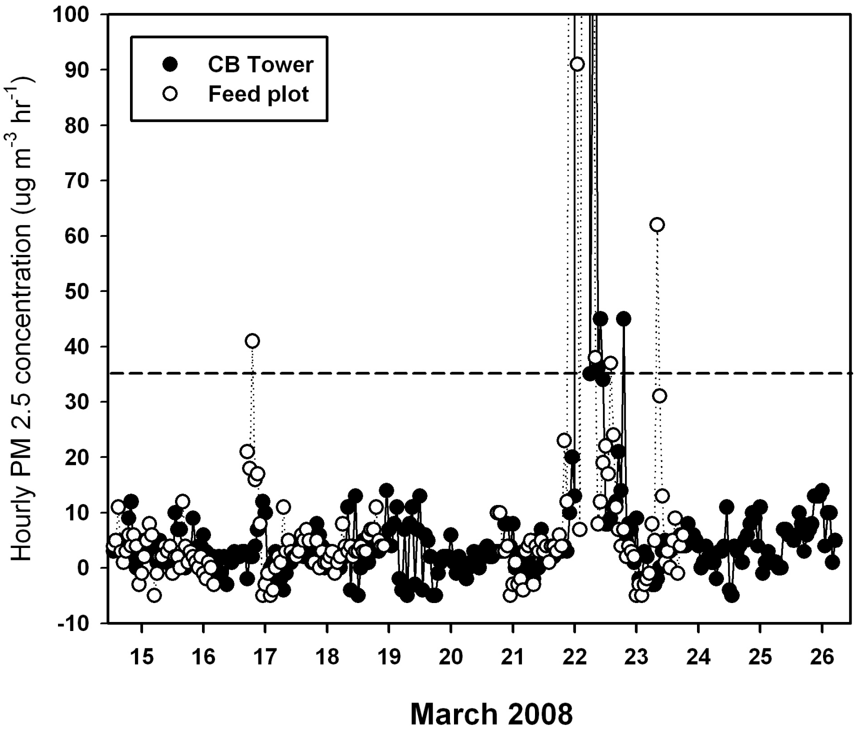

Fig. 8. Inset of hourly PM 2.5 concentrations at the Cedar Bridge flux tower (●) and the adjacent feed plot (○) from March 15th to 26th, 2008. Scale is -10 to 100 µg m^{-3}, and misses the large peaks during the prescribed fire on March 22, 2008, shown in Fig. 7. The dashed line indicates the current EPA PM 2.5 standard for a 24-hour period.

Discussion

The Pinelands National Reserve contains some of the most hazardous fuel types in the Northeastern US (Wright *et al*. 2007; Duvenek and Patterson 2007). We sampled a wide range of fuel loadings in the four upland forest communities, with time since last prescribed burn or wildfire ranging from two years in a fuel control strip, to ca. 45 years at two 'old' stands that had not burned since 1962 (prescribed burn) and 1963 (wildfire in April 1963). While the quantification of fuels in 1 m^2 plots is relatively straightforward, scaling 10 to 20 randomly located plots to the stand level introduces variability into the fuel loading estimates. Likewise, post-burn measurements made within the same stands in a similar manner but not made in the same spatial location as the pre-burn measurements potentially introduces some error into the estimation of consumption losses.

Fuel loading and consumption estimates reported here are generally consistent with previous work in the Pinelands (Burns 1952; Wright *et al*. 2007; Clark *et al*. 2009). For example, Wright *et al*. (2007) show similar forest floor loading for 10-hour fuels (1.86 ± 1.15 t ha^{-1}, t = 1.143, P = 0.246) and understory vegetation in the Pitch Pine photoseries data for the Pinelands. However, 1-hour fuel loading estimates were lower than our values (5.47 ± 1.57 t ha^{-1}, t = 4.770, P < 0.001), likely due to their use of fuel bed depth and bulk density estimates to calculate loading, rather than the use of fuel mass measurements as in our research. Burns (1952) sampled a number of prescribed burn blocks where fires had been conducted over a 15-year interval, and reported that loading of fuels on the forest floor was a strong function of prescribed burn history (Total fuel loading = -2.80 (number of prescribed burns) + 40.41 ton ha^{-1}, $r^2 = 0.79$, $P < 0.01$). His mass estimates for the forest floor were higher than those reported here, but he included duff mass in the O horizon with 1-hour and 10-hour fuel estimates. Taken together, our estimates for 1-hour and 10-hour fuels on the forest floor are intermediate between the Photoseries data reported by Wright *et al*. (2007) and those reported in Burns (1952).

Fuel loading, spatial arrangement, fuel moisture content, prevailing meteorological conditions (relative humidity, temperature, wind speed), and ignition patterns are critical factors controlling fuel consumption during prescribed fire treatments. Dry fuels enable ignition and subsequent fuel consumption. Meteorological conditions then become key factors in controlling fire spread rates and the amount of fuel consumed during prescribed fires. However, our results indicate that over the range of conditions that occurred during operational prescribed fires conducted by the NJFFS that we quantified from 2004 to 2009, initial fuel loading had an overriding effect on the amount of fuel consumed. Prescribed burns are conducted within a relatively narrow window of appropriate meteorological conditions, with air temperature typically not exceeding 16 °C, and RH above 40%. In our data, fuel moisture contents were variable, and soil temperature ranged from ca. 0 to 11 °C. Thus, it may be incorrect to apply the results reported here to prescribed fires conducted outside of this set of conditions.

In contrast to our results, Goodrick *et al.* (2010) reported a relatively weak relationship between initial fuel loading and fuel consumption ($r^2 = 0.34$) for a range of studies conducted in Longleaf pine-dominated stands in South Carolina. When components of the National Fire Danger Rating System, primarily the Burning Index (BI) were included in their regression equations, predictive power improved considerably ($r^2 > 0.8$).

Mean fuel consumption during operational prescribed fires reported here was much less than that measured during a large crowning prescribed fire that was conducted on March 21, 2008 near the site of the Warren Grove wildfire. Pre- and post-burn measurements indicated that this stand did have relatively high loading, but was reflective of much of the area burned in the 2007 wildfire, most of which had not burned since the early 1970's (see Figure 1 in Clark *et al*. 2009).

We used standard emission factors to calculate the release of PM 2.5 and other constituents from prescribed fires. Factors which affect the actual release rates of PM 2.5 and other criterion pollutants include fuel moisture content and the efficiency of fuel combustion, both of which can affect the balance between flaming and smoldering combustion (see Table 2). Many of the fuel beds on forest floor sampled in these upland forests were generally uniform due to repeated prescribed fires conducted since the 1950's, and emissions occurred over a relatively short period of time. The undifferentiated organic matter layer was rarely consumed, in contrast to the burning of thick duff and organic matter layers in lowland forests. Slow consumption of organic material lower in the forest floor of lowland and wetland forests can lead to much greater emissions of PM 2.5, due to smoldering over longer time periods (e.g., Mickler *et al*. 2010).

Total annual emissions from prescribed burns conducted by NJFFS in the Pinelands between 2002 and 2008 averaged 365 tons PM 2.5 $year^{-1}$, and ranged from 256 to 611 tons PM 2.5 yr^{-1}. When considered in the context of overall total PM 2.5 emissions in New Jersey (29,103 tons PM 2.5 yr^{-1} in 2002), prescribed fires conducted in the Pinelands contributed an estimated 1.3 %, with a range of 0.9 to 2.1 % of total PM 2.5 emitted to the atmosphere by all sources in the state in 2002. The three largest sources in 2002 were residential wood combustion (9,363 tons PM 2.5 yr^{-1}), restaurant operations (2,226 tons PM 2.5 yr^{-1}), and heavy duty diesel vehicles (1,329 tons PM 2.5 yr^{-1}). Total estimate PM 2.5 emissions from the Warren Grove wildfire in 2007 was estimated at 1,084 ± 292 tons PM 2.5, and represented 3.7% of total annual PM 2.5 emissions in New Jersey in 2002. When considered on a daily (24-hour) basis, emissions of PM 2.5 over the two major burning days during the Warren Grove fire (May 15th and 16th, 2007) were 6.7 times greater than the mean daily emissions reported for 2002 in New Jersey.

PM 2.5 Concentrations in Ambient Air

The temporal scales (sampling period, duration and frequency) of measurement are important for the assessment of human exposure to PM 2.5 and other EPA criterion pollutants. In many areas, PM 2.5 concentrations have been measured over a number of years, providing estimates of daily, seasonal and annual averages. In general, seasonal variations in PM 2.5 at many sites can be attributed to fluctuations in meteorological factors. In contrast, diurnal variations in PM 2.5 mainly depend on the fluctuations in the intensity of local pollution sources, e.g., fires, roads, air traffic, etc.

Ambient PM 2.5 concentrations in the Pinelands were highest on average from June through August, and were associated with photochemical smog and regional trends in PM 2.5 dispersion. Ambient ozone levels are also higher at this time of year, as a component of photochemical smog. Thus, trends in ambient PM 2.5 concentrations reflected seasonal synoptic weather patterns, especially patterns of mean above-canopy windspeed and direction, incident solar radiation, and air temperature. The patterns of seasonal variation in PM 2.5 concentrations in ambient air reported here for the Pinelands are consistent with data collected at Brigantine, NJ, which shows a similar summer peak in PM 2.5; seasonal daily (24-h) averages for Brigantine from 2000-2004 were 9.32 ± 4.78 μg m^{-3} for January to May, 13.86 ± 10.64 μg m^{-3} for June to August, and 8.28 ± 5.09 μg m^{-3} in September to December. Patterns in seasonal ambient PM 2.5 concentrations reported here are also consistent with a second PM 2.5 monitoring station to the east of the Pine Barrens in Toms River, NJ, where annual PM 2.5 concentrations averaged 11.8 μg m^{-3}.

Our data from the prescribed fires near the Cedar Bridge fire tower in March 2008 show that PM 2.5 concentrations at prescribed fires can be very high during burning operations, but also that plume dispersion occurs rapidly during the relatively windy periods in late winter and early spring, resulting in relatively low PM 2.5 emissions in less than 24 hours. Although a regional analysis of the impacts of prescribed burning on PM 2.5 concentrations in ambient air is beyond the scope of this research, other regions in the US have reported the effects of prescribed burns and wildfires on ambient PM 2.5 concentrations. For example, Zeng *et al*. (2008) reported that prescribed burning in the southeast US during the spring can account for up to 15% of total PM production, and that ambient PM 2.5 concentrations across the region can increase by 25 μg PM 2.5 m^{-3} during periods of intense prescribed burning. Jaffe *et al*. (2008) found statistically significant relationships between the area burned and seasonal PM 2.5 concentrations in ambient air, and between the amount of total fuel burned and seasonal PM 2.5 concentrations in ambient air in the western US. They used these relationships to calculate the addition amount of PM2.5 due to fires in Regions 1-5 in the western states, and reported summer-long enhancement of PM2.5 due to fires is 1.84, 1.09, 0.61, 0.81, and 1.21 μg PM 2.5 m^{-3}, respectively. Additional PM 2.5 levels were approximately twice these values during large fire years.

We are currently developing a more accurate GIS database of prescribed fire treatments conducted by the NJFFS and fire managers at Fort Dix from 1990-present, located in the forested areas of the Pine Barrens described above for fuel loading measurements (e.g., Clark *et al.* 2009). These will be used to estimate average amounts of fuel consumed more accurately than the method used above, and we can then refine our estimates of average annual emissions from stands burned by the NJFFS and federal wildland fire managers. In addition, we plan to monitor and model PM 2.5 emissions from prescribed fires more accurately in 2011-2013 (e.g., Heilman *et al*. 2010).

Summary

Consumption of 1-hour and 10-hour fuels on the forest floor and understory shrubs and oaks were quantified in 24 operational prescribed fires conducted by the NJFFS in the Pinelands of New Jersey. Emissions were calculated using emission factors, and atmospheric PM 2.5 measurements were made in ambient air and during prescribed fires.

Pre-burn 1-hour and 10-hour fuel loading was greater in Pitch pine - scrub oak stands than in stands that were characterized with a greater biomass of overstory oaks. Across all prescribed burns measured, consumption of fuels averaged 6.1 ± 3.2 t ha^{-1} on the forest floor and 3.5 ± 2.5 t ha^{-1} for understory vegetation, and consumption of both were strong linear functions of initial fuel loading. PM 2.5 emissions averaged 46 ± 15 kg PM 2.5 ha^{-1} from oak-dominated stands and 126 ± 33 kg PM 2.5 ha^{-1}from pine-dominated stands. For comparison, total fuel combustion and PM 2.5 release calculated from the Warren Grove wildfire in 2007 averaged 18.6 t ha^{-1} and 172 $\pm$ 46 kg PM 2.5 ha^{-1}. Our results indicate that forest floor consumption is often the predominate site of PM 2.5 production during prescribed fires, even during crowning fires in Pitch pine -scrub oak stands.

Estimated annual PM 2.5 emissions from prescribed fires were a small fraction of annual emissions from all sources in the state. Calculated PM 2.5 emissions from the Warren Grove wildfire in 2007 were 2 to 3 times greater than average annual emissions from prescribed burns in the Pinelands. During a series of prescribed burns in 2008, measured air concentrations spiked and then dropped exponentially to below 35 μg m^{-3} within 11 hours following the burns. Our research facilitates a more accurate estimate of PM 2.5 production during operational fuel reduction activities, based on knowledge of pre-burn fuel loading. Our data also suggests that annual emissions of PM 2.5 from prescribed fires would be less than years where wildfires burned > ca. 5000 ha in the Pinelands. Thus, it is likely that in addition to reducing wildfire risk to property and human welfare, prescribed burning may actually reduce human exposure to hazardous air pollutants.

References

Battye W, Battye R (2002) Development of emissions inventory methods for wildland fire. ‘Final Report Contract 68-D-98-046, US Environmental Protection Agency.’ (Research Triangle Park, NC)

Burns PY (1952) Effect of fire on forest soils in the Pine Barren region of New Jersey. *Yale School Forestry Bull.* **57**, 1-50.

Clark KL, Skowronski N, Hom J, Duveneck M, Pan Y, Van Tuyl S, Cole J, Patterson M, Maurer S (2009) Decision support tools to improve the effectiveness of hazardous fuel reduction treatments. *International Journal of Wildland Fire* **18**, 268-277.

Clark KL, Skowronski N, Hom J (2010) Invasive Insects Impact Forest Carbon Dynamics. *Global Change Biology* **16**, 88-101.

Duveneck MJ, Patterson WA (2007) Characterizing canopy fuels to predict fire behavior in pine stands. *Northern Journal of Applied Forestry* **24**, 65-70.

Goodrick SL, Shea D, Blake J (2010) Estimating fuel consumption for the Upper Coastal Plain of South Carolina. *Southern Journal of Applied Forestry* **34**, 5-12.

Heilman W, Skowronski N, Bian X, Shadbolt R, Zhong S, Clark K, Charney J, Bohrer G, Kiefer M, Hom J. (2010) Development and validation of modeling tools for predicting smoke dispersion during low-intensity fires. In 'Proceedings of third fire behavior and fuels conference,' 25-29 October 2010 Spokane, WA. CD-ROM. Abstract 3.18. International Association of Wildland Fire. (Birmingham, AL)

Jaffe D, Hafner W, Chand D, Westerling A, Spracklen D (2008) Interannual variations in PM2.5 due to wildfires in the western United States. *Environmental Science and Technology* **42**, 2812-2818.

Lathrop R, Kaplan MB (2004) New Jersey land use/land cover update: 2000-2001. 'New Jersey Department of Environmental Protection.' (Trenton, NJ).

Little S (1998) Fire and plant succession in the New Jersey Pine Barrens. In 'Pine barrens: ecosystem and landscape.' (Ed RTT Forman) pp. 297-314. (Rutgers University Press, New Brunswick, NJ).

Little S, Moore EB (1949) The ecological role of prescribed burns in the pine-oak forests of southern New Jersey. *Ecology* **30**, 223-233.

McCormick J, Jones L (1973) 'The Pine Barrens: Vegetation geography.' Research Report Number 3, New Jersey State Museum. (Trenton, NJ).

Mickler R, Geron C, Rorig M (2010) Predicting prescribed and wildland fire behavior in deep organic soils In 'Proceedings of 3rd fire behavior and fuels conference,' 25-29 October 2010 Spokane, WA. (Ed DD Wade) CD ROM. International Association of Wildland Fire. (Birmingham, AL)

Skowronski NS, Clark KL, Duveneck M, Hom J (2010) Three-dimensional canopy fuel loading predicted using upward and downward sensing lidar systems. *Remote Sensing of Environment*, doi:10.1016/j.rse.2010.10.012.

Skowronski N, Clark K, Nelson R, Hom J, Patterson M (2007) Remotely sensed measurements of forest structure and fuel loads in the Pinelands of New Jersey. *Remote Sensing of Environment* **108**, 123-129.

Tedrow JCF (1986) 'Soils of New Jersey.' New Jersey Agricultural Experiment Station publication A-15134-1-82, Krieger Publishing Co. (Malabar, FL).

Tian D, Wang Y, Bergin M, Hu Y, Liu Y, Russell AG (2008) Air quality impacts from prescribed forest fires under different management practices. *Environmental Science and Technology* **42**, 2767-2772.

US EPA (1997a) 40 CFR, Part 50, Federal Register Vol. 62, No. 138.

US EPA (1997b) 40 CFR, Part 53, Federal Register Vol. 62, No. 138.

US EPA (1997c) 40 CFR, Part 58, Federal Register Vol. 62, No. 138.

Wright CS, Ottmar RD, Vihnanek RE (2007) 'Stereo photo series for quantifying natural fuels. Volume VIII: Hardwood, pitch pine, and red spruce/basam fire types in the northeastern United States.' PMS 840. National Wildfire Coordinating Group, National Interagency Fire Center. (Boise, ID).

Zeng T, Wang Y, Yoshida Y, Tian D, Russell AG, Barnard WR (2008) Impacts of prescribed fires on air quality over the southeastern United States in spring based on modeling and ground/satellite measurements. *Environmental Science and Technology* **42**, 8401–8406.