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Real-time and time-integrated $PM_{2.5}$ and CO from prescribed burns in chipped and non-chipped plots: firefighter and community exposure and health implications

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In this study, smoke data were collected from two plots located on the Francis Marion National Forest in South Carolina during prescribed burns on 12 February 2003. One of the plots had been subjected to mechanical chipping, the other was not. This study is part of a larger investigation of fire behavior related to mechanical chipping, parts of which are presented elsewhere. The primary objective of the study reported herein was to measure $PM_{2.5}$ and CO exposures from prescribed burn smoke from a mechanically chipped vs. non-chipped site. Ground-level time-integrated $PM_{2.5}$ samplers ($n=9$/plot) were placed at a height of 1.5 m around the sampling plots on the downwind side separated by approximately 20 m. Elevated time-integrated $PM_{2.5}$ samplers ($n=4$/plot) were hung atop $\sim$30 ft poles at positions within the interior of each of the plots. Real-time $PM_{2.5}$ and CO data were collected at downwind locations on the perimeter of each plot. Time-integrated perimeter 12-h $PM_{2.5}$ concentrations in the non-chipped plot (AVG 519.9 $\mu g/m^3$, SD 238.8 $\mu g/m^3$) were significantly higher (1-tail P-value 0.01) than those at the chipped plot (AVG 198.1 $\mu g/m^3$, SD 71.6 $\mu g/m^3$). Similarly, interior time-integrated 8-h $PM_{2.5}$ concentrations in the non-chipped plot (AVG 773.4 $\mu g/m^3$, SD 321.8 $\mu g/m^3$) were moderately higher (1-tail P-value 0.06) than those at the chipped plot (AVG 460.3 $\mu g/m^3$, SD 147.3 $\mu g/m^3$). Real-time $PM_{2.5}$ and CO data measured at a position in the chipped plot were uniformly lower than those observed at the same position in the non-chipped plot over the same time period. These results demonstrate that smoke exposures resulting from burned chipped plots are considerably lower than from burned non-chipped plots. These findings have potentially important implications for both firefighters working prescribed burnings at chipped vs. non-chipped sites, as well as nearby communities who may be impacted from smoke traveling downwind from these sights.
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Introduction

Prescribed burning is a beneficial tool for reducing wildfire hazard and competing vegetation, and for improving forage value of the forests (Reinhardt, 1991), (URL: www.epa.gov/ttn/chief/ap42/ch13/final/c13s01.pdf). Southern land managers use prescribed fire to treat 6–8 million acres (2–3 million hectares) of forest and agricultural lands in the Southern states each year (Wade et al., 2000), more than any other comparable area in the US. The potential impact of smoke from prescribed burning on occupational and community smoke exposures and related health effects is a growing concern. For instance, several studies have demonstrated that prescribed burning (Yanosky, 2001; Carlton et al., 2003; Carlton, 2004) and wildland fires (Materna et al., 1992; Reinhardt and Ottmar, 2000; Reinhardt et al., 2000) can result in firefighter personal smoke exposures high enough to warrant occupational health concern. Further, several studies have demonstrated or suggested adverse firefighter health effects from these increased exposures (Letts et al., 1991; Rothman et al., 1991; Liu et al., 1992; Serra et al., 1996; Betchley et al., 1997; Slaughter et al., 2004). A number of studies have also demonstrated or suggested adverse health effects in individuals from communities exposed to smoke from wildland fires (Duclos et al., 1990; Sorenson et al., 1999; Mott et al., 2002; Sutherland et al.,

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2005), although other more limited and less generalizable studies have found little to no association between these exposures and health (Copper et al., 1994; Smith et al., 1996; Jalaludin et al., 2000).

In addition to prescribed burning, mechanical chipping/shearing is another method for treating and managing competing and unwanted vegetation. Mechanical chipping uses track vehicles, typically with fixed or flail blades mounted on a forward rotating drum to pulverize woody debris and mid-story trees without doing much harm to soils or plant roots. (http://www.fs.fed.us/r6/nr/fid/pubsweb/94mech.pdf#xml = http://www.fs.fed.us/cgi-bin/texis/searchallsites/search.allsites/xml.txt?query = mechanical + chipping&db = allsites&id = 41c00c80) (Glitzenstein, 2005), It is increasingly used for hardwood mid-story control and fuel modification objectives (Ottmar et al., 2001). While mechanical chipping can reduce wildfire threats, Southern land managers will continue to rely upon periodic prescribed fires to control the risk of wildfires on chipped plots. Commenting on this technique, Ottmar et al. (2001) point out that "If the biomass is spread across the ground, additional litter fuels emission reductions are not achieved if the litter is consumed in either a prescribed or wildland fire" (Ottmar et al., 2001). The influence of chipping on smoke production and corresponding occupational and community exposures from prescribed fires has not been evaluated.

In this study, smoke data were collected from two plots located on the Francis Marion National Forest (FMNF) in South Carolina during prescribed burns on 12 February 2003. One of the plots had been subjected to mechanical chipping, the other had not. The main a-*priori* rationale for this study was related to the large amount of heavy, that is 1000-h[1], fuels still on the forest floor since 1989 from Hurrican Hugo (Achtemeier et al., 2006; Glitzenstein et al., 2006). As smoke from Hugo logs appeared to be a major contributor to United States Forest Service (USFS) smoke problems post burns, it was hoped that by pulverizing these logs chipping would solve the residual smoke problem. This assumption may or may not have been supportable scientifically, but it was the operational assumption and a major reason for large expenditures on chipping operations. This study is part of a larger investigation of fire behavior related to mechanical chipping, parts of which are presented elsewhere (Achtemeier et al., 2006; Glitzenstein et al., 2006; Streng et al., 2006) (Figure 1). The primary objective of the study reported herein was to compare $PM_{2.5}$ and CO levels in prescribed burn smoke from a mechanically chipped vs. a non-chipped site. Results of this research may contribute to our understanding of the potential benefits of chipping as a land management practice, including implications for occupational and community smoke exposures and related health effects.

[1]1000-h fuels: 1000 refers to the number of hours of drying post saturating rain necessary before that particular fuel diameter class reaches 63% of equilibrium moisture value. In practical terms this is the timelag before the fuel dries sufficiently to burn. It is the largest diameter class of downed fuels typically recognized in fuel sampling.

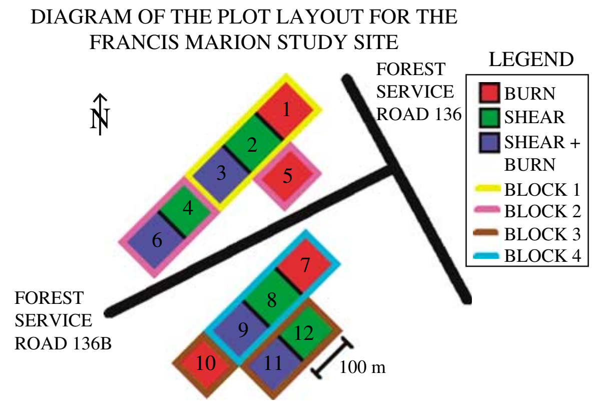

Figure 1. Diagram of plot layout for Francis Marion 2003 (source: Achtemeier et al., 2006).

Methods

Study design

Smoke data were collected from two 100 m by 100 m plots at FMNF during prescribed burns on 12 February 2003, one which had been subjected to mechanical chipping (Plot 6) and one which had not (Plot 1) (Figure 1) (Achtemeier et al., 2006; Glitzenstein et al., 2006). The plots were separated by 300 m of chipped area (Figure 1). The area in which the plots were located had not been burned since prior to Hurricane Hugo in 1989, a period of 14 years. Thus, fuel accumulations in the plots were substantial, consisting mostly of pine litter and downed woody material including large partially decomposed logs persisting since the hurricane (Achtemeier et al., 2006). There were comparable quantities of biomass present in both plots (Achtemeier et al., 2006). A more detailed explanation of the methods of the overall study design and the plot preparation is provided elsewhere (Achtemeier et al., 2006; Glitzenstein et al., 2006).

Time-integrated $PM_{2.5}$ sampling

Fine particulate ($PM_{2.5}$) samples were collected by SKC pumps drawing air at a rate of 4.0 l/min through a BGI KTL cyclone and by SKC Air Check 2000 pumps drawing air at a rate of 1.5 l/min through a BGI Triplex cyclone (SKC, Waltham, MA; BGI, Waltham, MA). Both cyclone types used 37 mm Teflo filters (Pall Co.) to which the particles adhered. A dense line of SKC Air Check 2000 pumps was positioned along the downwind side and part way up the adjacent sides of each plot (Figures 2 and 3). Pumps were

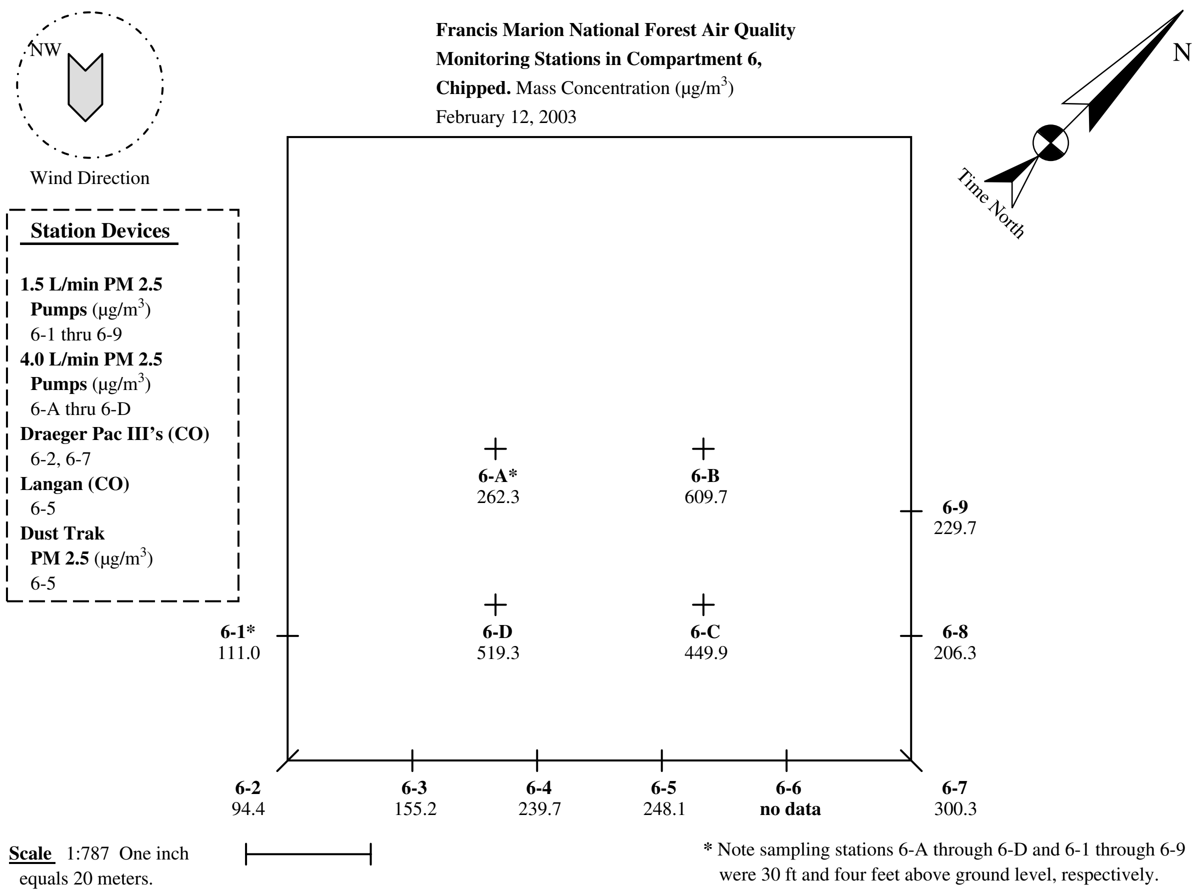

Figure 2. Time-integrated $PM_{2.5}$ measurements at interior and perimeter Sampling locations in compartment 6 (Chipped Plot).

separated by 20 m and the cyclones were hung 1.5 m off the ground. In addition to the ground level samplers, SKC 4.0 l/min pumps were hung atop 30 ft poles at four positions within the interior of each smoke monitoring plot (Figures 2 and 3).

An additional $PM_{2.5}$ sampling station was located midway (i.e. 150 m) between the two plots (in the center of plot 3 in Figure 1). Real-time $PM_{2.5}$ and CO instruments (described below) and a weather station were co-located in this location. Data from this site was used to check for cross-contamination between the two plots. The methodology and results for the weather station are presented elsewhere (Achtemeier et al., 2006).

All interior pumps were set to run for the estimated ignition and burn time (1400–2200). All perimeter pumps and the pump at the check location were set to run throughout the night (1800–0600) in order to catch smoke produced during the active burning and smoldering phases. Before and after sampling, the flow rate of the pumps was calibrated using a Delta Cal calibrator. At the end of the sampling period, the filters were removed from the cyclones, put in boxes, sealed, refrigerated, and returned to laboratory for gravimetric analysis.

In preparation for gravimetric analysis, filters were stored under controlled climate conditions (20.6 ± 1.4°C) for at least 48 h prior to pre-weighing and for at least 48 h prior to initial post-weighing. Filters were weighed using a Cahn C-35 microbalance with a sensitivity of $\pm 1\,\mu g$ and adjusted for buoyancy following standard methods (US Environmental Protection Agency, 2003). The sample volume was obtained by multiplying sampling time and the average of the on flow and off flow rates. $PM_{2.5}$ concentration was calculated as the weight difference between the filter pre-weights and the post-weights divided by the sample volume.

Continuous $PM_{2.5}$ and CO sampling

Continuous aerosol $PM_{2.5}$ data were collected by TSI DustTrak monitors (TSI Inc., St Paul, MN). Draeger PAC III and Langan instruments were co-calibrated before this experiment and used for real time CO data collection (SKC, Waltham, MA; Lee Langan, San Francisco, CA). A Langan CO monitor and a TSI DustTrak were positioned along the downwind sides of both plots (Figures 2 and 3). PAC IIIs were placed at the downwind corners of the plots (Figures 2 and 3). A DustTrak $PM_{2.5}$ monitor and a Langan CO monitor were also co-located with the SKC pump and the

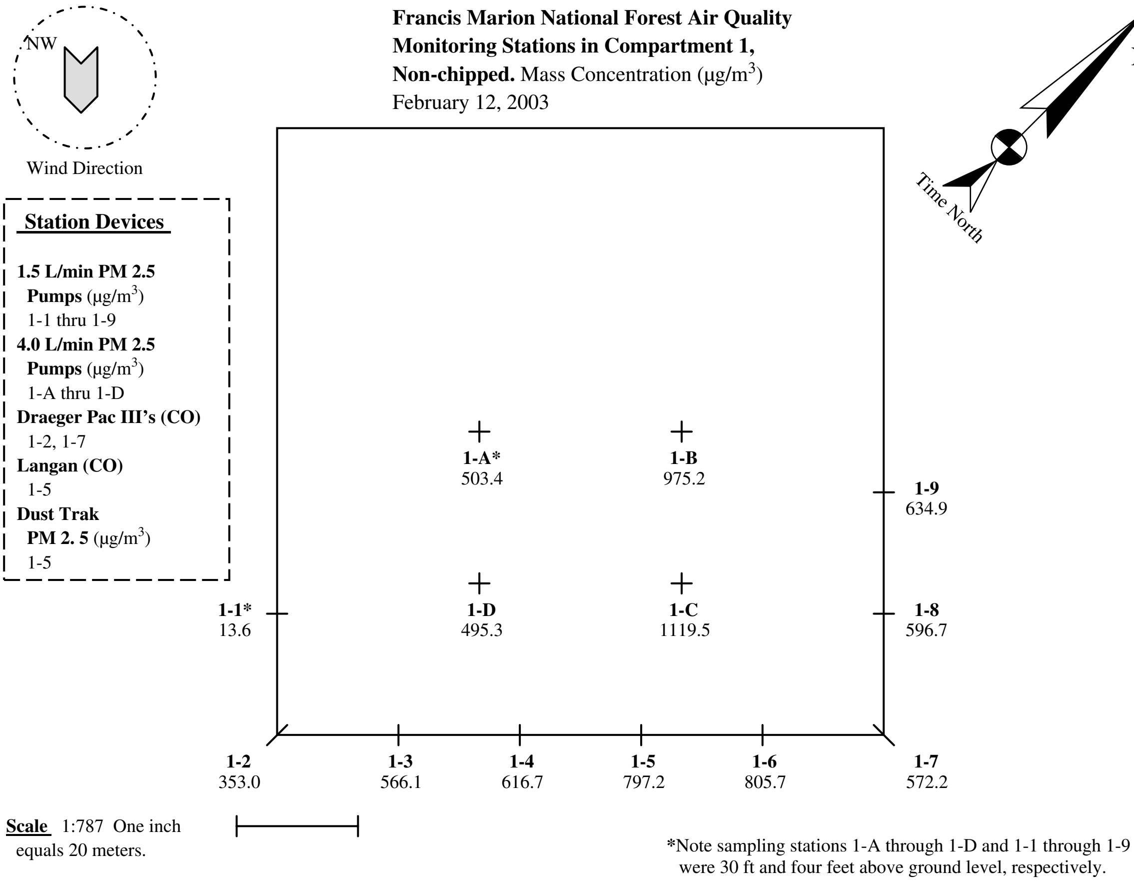

Figure 3. Time-integrated $PM_{2.5}$ measurements at interior and perimeter sampling locations in compartment 1 (Non-Chipped Plot).

weather station described above at the check location midway between the two smoke plots.

Data analysis

Our hypothesis was that smoke production from a prescribed burn, measured by $PM_{2.5}$ and CO, would be lower in the chipped plot vs. the non-chipped plot. To test our hypothesis, we used a simple one tail Student's *t*-test to compare the time-integrated $PM_{2.5}$ levels measured along on the perimeter (ground level) and interior (elevated to 30 ft) from the chipped vs. the non-chipped plot. In addition, we compared real-time perimeter $PM_{2.5}$ and CO in the chipped vs. the non-chipped plot.

Results

Time-integrated $PM_{2.5}$ results are presented in Figures 2 and 3 and Table 1. The time-integrated $PM_{2.5}$ sample for Plot 6 at location 6 (location 6–6) was lost due to instrument malfunction. This data point as well as the parallel sample for Plot 1 (location 1–6), were excluded from the data analysis, although the data for location 1–6 shown in Figure 3. Perimeter 12-h $PM_{2.5}$ concentrations in the non-chipped plot (AVG 519.9 $\mu g/m^3$, SD 238.8 $\mu g/m^3$) were substantially and statistically significantly (*P*-value 0.01) greater than those at the chipped plot (AVG 198.1 $\mu g/m^3$, SD 71.6 $\mu g/m^3$). Similarly, interior 8-h $PM_{2.5}$ concentrations in the non-chipped plot (AVG 773.4 $\mu g/m^3$, SD 321.8 $\mu g/m^3$) exceeded those in the chipped plot (AVG 460.3 $\mu g/m^3$, SD 147.3 $\mu g/m^3$), although the means were only marginally different (*P*-value 0.06).

A more detailed temporal picture of $PM_{2.5}$ emissions at ground level in the non-chipped plot is provided by the DustTrak located at position 1 to 5 on the downwind side of the plot (Figure 4). The record began at 1500 and terminated near midnight on 12 February 2003. A sharp peak in concentrations occurred when smoke from the broad backfire impacted the instruments. $PM_{2.5}$ concentrations briefly exceeded 100 mg/m^3 during this period. Concentrations remained elevated during the active flaming stage of the burn, then fell to less than 2 mg/m^3 after 1830 EST and then to near background levels by 1930 EST. Concentrations recovered to 5–10 mg/m^3 after 1930 EST.

Figure 4 also shows the real-time $PM_{2.5}$ data measured at position 6–5 in the chipped plot. $PM_{2.5}$ concentrations

Table 1. Time-integrated $PM_{2.5}$ measurements at all interior, perimeter, and check sampling locations

Sampling location	Delay start/end time	Elapsed time (min)	Average flow (l.p.m.)	Mass concentration ($\mu g/m^3$)
1–1	1800–0600	720	1.528	13.6
1–2	1800–0600	720	1.515	353.0
1–3	1800–0600	720	1.508	566.0
1–4	1800–0600	720	1.510	616.7
1–5	1800–0600	720	1.495	[a]
1–6	1800–0600	720	1.510	805.7
1–7	1800–0600	720	1.515	572.2
1–8	1800–0600	720	1.523	596.7
1–9	1800–0600	720	1.504	634.9
			Avg	519.9
			SD	238.8
			Max	805.7
			Min	13.6
6–1	1800–0600	720	1.496	111.0
6–2	1800–0600	720	1.509	94.3
6–3	1800–0600	720	1.488	155.2
6–4	1800–0600	720	1.498	239.7
6–5	1800–0600	720	1.501	248.1
6–6	1800–0600	720	1.514	
6–7	1800–0600	720	1.510	300.3
6–8	1800–0600	720	1.502	206.3
6–9	1800–0600	720	1.498	229.7
			Avg	198.1
			SD	71.6
			Max	300.3
			Min	94.3
1-A	1400	480	4.027	503.4
1-B	1400	480	4.012	975.2
1-C	1400	480	3.993	1119.5
1-D	1400	480	4.008	495.3
			Avg	773.4
			SD	321.8
			Max	1119.5
			Min	495.3
6-A	1400	480	3.977	262.3
6-B	1400	480	4.018	609.7
6-C	1400	480	4.057	449.9
6-D	1400	480	3.971	519.3
			Avg	460.3
			SD	147.3
			Max	609.7
			Min	262.3
Check	1800–0600	720	1.502	178.0

[a]Position 1–5 had a $PM_{2.5}$ value of 797.2 $\mu g/m^3$, but is not included in the statistical analysis because its counterpart in plot 6 (position 6–5) does not have a valid data point.

observed here were uniformly lower than those observed at position 1–5 in the non-chipped plot over the same time period. As in Plot 1, the Plot 6 trace indicated an initial spike in concentrations when the back fire line was lit near the instrument. However, the magnitude of the spike was below the levels at Plot 1 during the corresponding time period.

The continuous CO and temperature results agree with the time-integrated and continuous $PM_{2.5}$ data (Figure 5). The temperature trace shows a jump of 7°C commensurate with the spikes in CO for both burns as heated air containing fire products passed by the samplers. Similarly, CO levels at position 6–2 (peak 6 ppm) and 6–7 (peak 13 ppm) in the

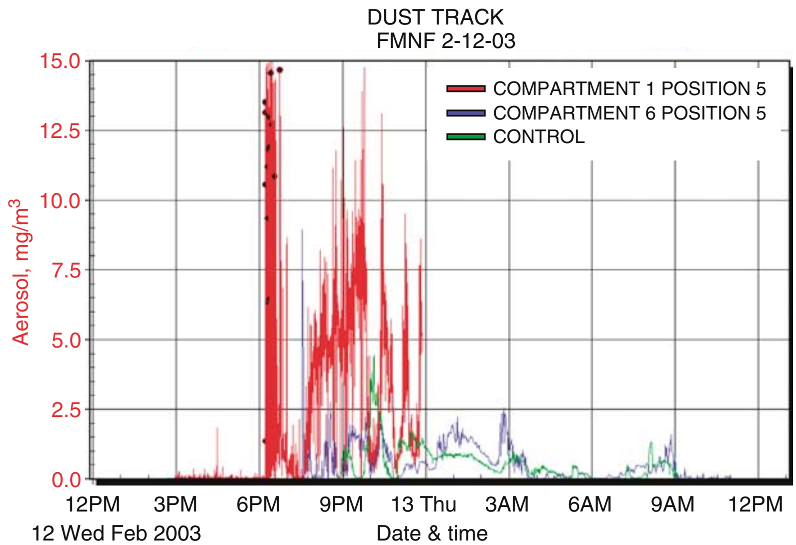

Figure 4. Real-time DustTrak $PM_{2.5}$ measurements at positions 1–5 (Plot 1), 6–5 (Plot 6) and the check location.

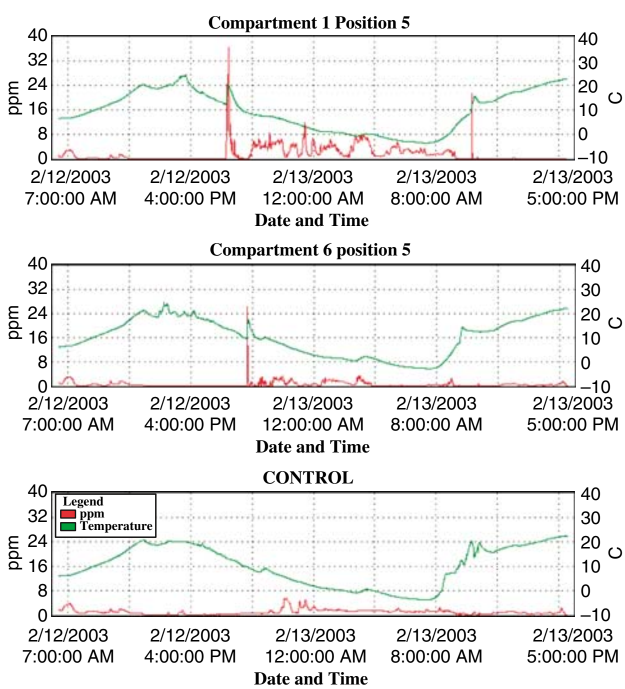

Figure 5. Real-time langan CO measurements at positions 1–5 (Plot 1), 6–5 (Plot 6) and the check location.

chipped plot were lower than corresponding samples at positions 1–2 (peak 29 ppm) and 1–7 (peak 17 ppm) in the non-chipped plot (Figure 6).

The chipped and non-chipped plots were oriented along a southwest/northeast axis based on the expectation that consistent winds from the northwest would minimize cross-contamination of smoke between the two test areas (Figure 1) (Achtemeier et al., 2006; Glitzenstein et al., 2006). Measurements from the check (control) site located midway between the two test plots suggest a modest degree of cross-contamination between the chipped and non-chipped plots. For instance, the 12-h $PM_{2.5}$ concentration at the check location was 178.0 $\mu g/m^3$, a value substantially above typical $PM_{2.5}$ levels (5–20 μg/m3) in this region. Consistent with this are the $PM_{2.5}$ and CO real-time plots presented in Figures 4 ($PM_{2.5}$), 5 and 6 (CO), respectively. The real-time $PM_{2.5}$ contamination began at 2100 EST, approximately 1.5 h after ignition and probably during the smoldering phase at Plot 6. The concentrations are low in comparison with post-burn smoldering $PM_{2.5}$ measurements at the non-chipped site (Plot 1) but are typical of $PM_{2.5}$ measurements at the chipped site (Plot 6) (Figure 4). Small CO concentrations were detected beginning at 2100 EST by the Langan CO monitor (Figure 5).

Discussion

This study is part of a larger investigation of fire behavior related to mechanical chipping, parts of which are presented elsewhere in complementary papers (Achtemeier et al., 2006; Glitzenstein et al., 2006; Streng et al., 2006). The smoke, meteorological, dispersion and modeling results are presented by Achtemeier et al. (2006), the fire behavior and fire management implications are presented by Glitzenstein et al. (2006) and effects on vegetation composition are discussed by Streng et al. (2006). In the current paper, we report elevated interior and ground-level perimeter smoke concentrations ($PM_{2.5}$ and CO) from prescribed burnings on mechanically chipped vs. non-chipped plots. The general conclusion supported in all three papers is that prescribed fires on

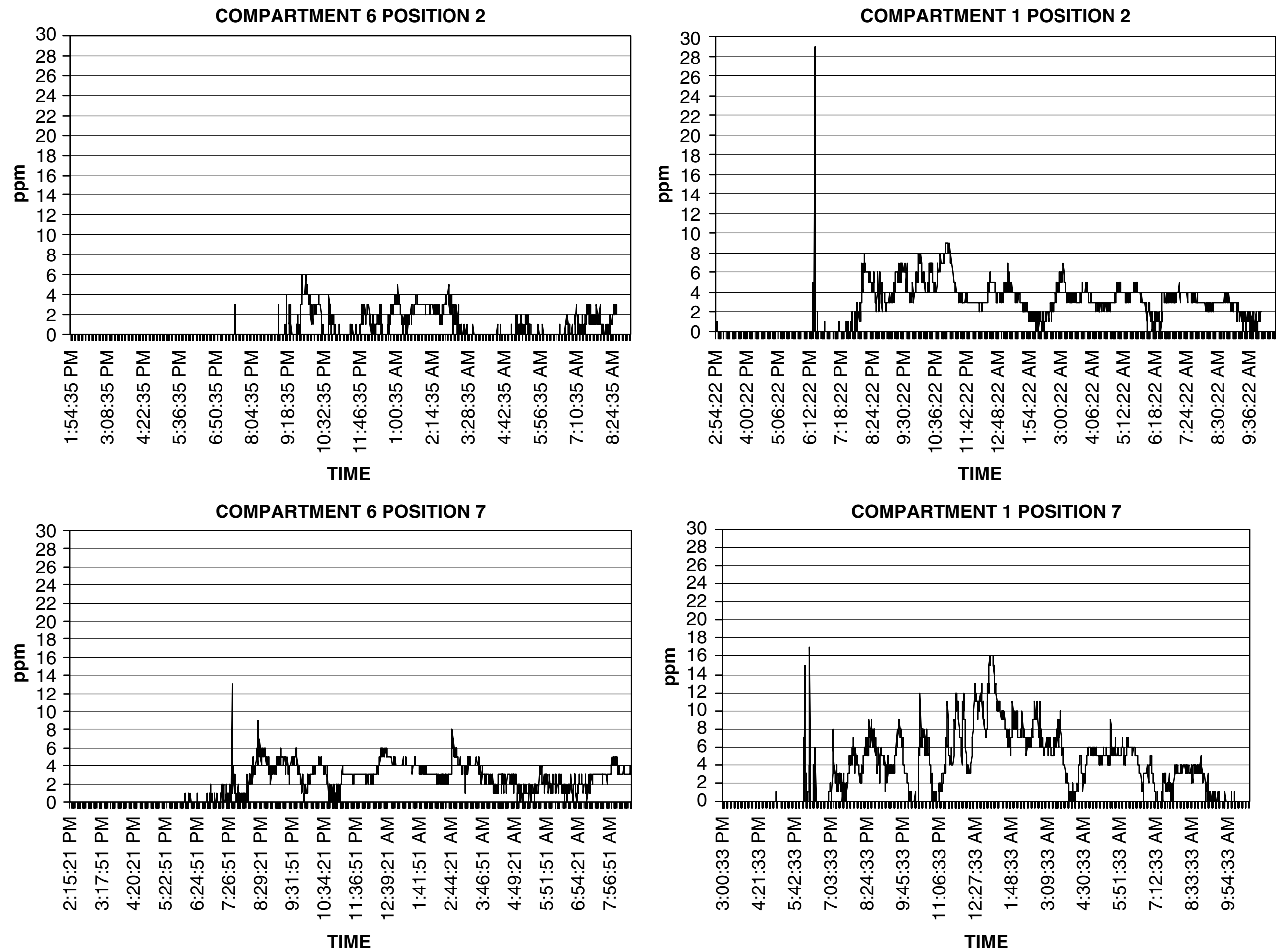

Figure 6. Real-time draeger CO measurements at positions 6–2 and 6–7 in the chipped plot and positions 1–2 and 1–7 in the non-chipped plot.

mechanically chipped plots produce less smoke than on non-chipped plots (Achtemeier et al., 2006; Glitzenstein et al., 2006; Streng et al., 2006).

As reviewed in Glitzenstein et al. (2006), chipping had multiple effects on smoke production in the current study. First, logs remaining on the ground from Hurricane Hugo were in fact pulverized in the chipping process. On the morning after the fires in the current experiment, significantly fewer 1000-h fuels were seen smoking in the chipped plots *versus* the non-chipped plots (Glitzenstein et al., 2006). Second, fuels overall were altered in the chipping process in such a way as to reduce total fuel consumption — thus reducing emissions. This result was indicated by the lesser burned areas and lower scorch in chipped plots vs. non-chipped plots and was supported by BehavePlus model predictions (Glitzenstein et al., 2006).

From an exposure assessment and human health perspective, the smoke reductions in the chipped vs. non-chipped plots in this study — $PM_{2.5}$ reduction of 40.5% at the elevated interior plot locations and 61.9% for the ground-level perimeter plot locations — are substantial. These results have important occupational (for firefighters working the prescribed burn) and community (for individuals present in communities nearby to prescribed burns) smoke exposure and health implications. The focus of the discussion in the current paper is on these occupational and community smoke exposure and health implications.

The $PM_{2.5}$ and CO values observed in this study are comparable to those found in other studies of ambient (Lee et al., in press) and occupational (Materna et al., 1992; Reinhardt and Ottmar, 2000; Reinhardt et al., 2000; Yanosky, 2001; Carlton et al., 2003; Carlton, 2004) monitoring during wildland fires or prescribed burns. Regarding occupational particulate standards, the Occupational Safety and Health Administration's (OSHA) standard for respirable dust (RD) is $5\,mg/m^3$ for 8 h (Federal Register, 1997). Respirable dust includes particulate matter $10\,\mu m$ or smaller in aerodynamic diameter. The National Institute of Occupational Safety and Health's (NIOSH), standard is $3\,mg/m^3$ for RD over 8 h. The American Conference of Governmental Industrial Hygienist's (ACGIH) Threshold Limit Value (TLV) standard is $3\,mg/m^3$ for RD over 8 h and

Table 2. Air quality standards

Pollutant	Averaging times	OSHA PEL[a]	NIOSH TLV[b]	ACGIH TLV[c]	USEPA NAAQS[d]	WHO[e]
Particulate matter 2.5 um or smaller in aerodynamic diameter ($PM_{2.5}$)	Annual (arithmetic mean)				$15.0\,\mu g/m^3$ [f]	
	24-h				$65\,\mu g/m^3$ [g]	
Respirable dust[h]	8-h	5 mg/m^3	3 mg/m^3	3 mg/m^3		
Respirable coal dust[h]						
Particulate matter 10 μm or smaller in aerodynamic diameter (PM_{10})	Annual (arithmetic mean)				$50\,\mu g/m^3$ [i]	
	24-h				$150\,\mu g/m^3$ [k]	
Carbon monoxide (CO)	8-h	50 ppm	35 ppm	25 ppm	9 ppm (10 mg/m^3)[j]	8.7 ppm (10 mg/m^3)
	1-h				35 ppm (40 mg/m^3)[j]	26 ppm (30 mg/m^3)
	Ceiling limit		200 ppm			

[a] Occupational Safety and Health Administration Permissible Exposure Limit (Occupational Safety and Health Administration (OSHA). Air Contaminants. Code of Federal Regulations Title 29, Part 1910.1000, Table Z-1, 1999).
[b] National Institute of Occupational Safety and Health Administration Threshold Limit Value (http://www.cdc.gov/niosh/pdfs/00-14075.pdf html).
[c] American Conference of Governmental Industrial Hygienists Threshold Limit Value (ACGIH. Documentation of the TLVs and BEIs, Vol. III, 6th ed. Cincinnati, Ohio, 1996).
[d] United States Environmental Protectin Agency National Ambient Air Quality Standards (US EPA (1997). 'National Ambient Air Quality Standards for Particulate Matter; Final Rule.' *Federal Register* 2).
[e] World Health Organization Air Quality Standards (*http://www.worldbank.org/html/fpdl/em/power/standards/airqstd.stm#who*: Source: World Bank, Environment Department, 'Initial Draft of Industrial Pollution Prevention and Abatement Handbook,' Jan 1995).
[f] To attain this standard, the 3-year average of the annual arithmetic mean $PM_{2.5}$ concentrations from single or multiple community-oriented monitors must not exceed $15.0\,\mu g/m^3$.
[g] To attain this standard, the 3-year average of the 98th percentile of 24-h concentrations at each population-oriented monitor within an area must not exceed $65\,\mu g/m^3$.
[h] Respirable dust and respirable coal dust includes particulate matter 10 um or smaller in aerodynamic diameter.
[i] To attain this standard, the expected annual arithmetic mean PM_{10} concentration at each monitor within an area must not exceed $50.0\,\mu g/m^3$.
[j] Not to be exceeded more than once per year.
[k] Not to be exceeded more than three times per year.

these standards are thought to be the most up to date (American Conference of Governmental Industrial Hygienists, 2003). However, these exposure standards were not intended to apply to wildland firefighting, where smoke concentrations are not subject to engineering controls. Nevertheless, based on the levels observed in the current study, it is not believed that firefighter personal occupational exposures for $PM_{2.5}$, had they been measured, would have approached but not exceeded the occupational standards presented in Table 2. However, based on the growing database linking comparatively low $PM_{2.5}$ exposures with a range of health effects, including mortality, it is our opinion that the OSHA, NIOSH, and ACGIH RD standards are not sufficient to protect firefighters from $PM_{2.5}$ exposures experienced during prescribed burns or fighting wildland fires. Further, the current study demonstrates that some measures, such as chipping, may result in reduced firefighter exposures.

Regarding ambient particulate standards, it is important first to remember that the occupational standards discussed above are designed to protect workers (presumably healthy) who are exposed only while at work (40-h per day, 2000 h per year). In contrast, the ambient standards discussed below are designed to protect sensitive receptors who are exposed 24-h per day, 365 days per year. That said, because previous studies have shown strong associations between mortality and fine particle exposure at levels considerably lower than those observed in this study, it is reasonable to compare the exposures observed in the current study to the US Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS) for particulate matter. The overwhelming amount of literature on health effects at low levels of fine particles caused the EPA to establish two new $PM_{2.5}$ standards: 24-h standard of $65\,\mu g/m^3$; ambient (annual) standard of $15\,\mu g/m^3$ (US Environmental Protection Agency, 1996). EPA's standard does not apply directly to the occupational setting but instead focuses on public health because these standards account for the health risk of those with pre-existing cardiac and pulmonary diseases, many of which are more prevalent among the elderly. However, firefighters are exposed to levels of woodsmoke well above $65\,\mu g/m^3$ on a regular basis and often for long periods on larger burns, suggesting the possibility that they may be at risk for adverse health effects from their occupational exposures. Similarly, it is plausible, although the data in this study are limited in making this case, that individuals living in communities near prescribed burns might be exposed to $PM_{2.5}$ levels exceeding the EPA's daily standard of $65\,\mu g/m^3$, suggesting the possibility that they too may be at risk for adverse health effect from their community exposures. The current study did not have any downwind $PM_{2.5}$ exposure data nor did we try to model downwind $PM_{2.5}$ exposure levels based on the data that we did collect — this was beyond the scope and objectives of the current study. However, models do exist that aid in estimating smoke concentrations downwind from prescribed burns (Lavdas, 1996; Achtemeier, 2005). Furthermore, two of the co-authors of this study, Naeher and Achtemeier, are involved in a multi-year project to collect PM data from 0.25 to 6 miles downwind from prescribed burns to validate point source smoke models (Achtemeier and Naeher, 2005).

Regarding occupational CO standards, the CO data measured in this study do not suggest that personal occupational CO exposures, had they been measured, would have exceeded any of the occupational standards presented in Table 2. The data do suggest, however, the possibility, if burns were of sufficient duration, that communities adjacent to prescribed burns could be exposed to CO levels exceeding the EPA and WHO 1-h CO standards. We do not wish to overstate either an occupational or community risk from CO because the potential occupational and community CO exposures in this study are not high. However, it should be pointed out that some epidemiologic studies have demonstrated that CO levels much lower than EPA standards were linked to elevated hospital admissions from cardiovascular diseases (Morris and Naumova, 1998; Yang et al., 1998), suggesting that even the moderate exposures observed in the current study may still pose health threats to firefighters and individuals in communities nearby to the burns. However, in these studies, it is unlikely that these health effects were due to CO itself. In these studies, CO is generally thought to be a marker or indicator pollutant for other combustion-related pollutants.

Despite the lack of replication and several sources of potential confounding in the smoke experiment, we believe that the smoke reductions observed on the chipped plots are valid. Supporting evidence from the larger study comes from several types of fire behavior and post-fire observations including: (1) somewhat taller flame lengths and higher scorch heights in the burn only plots; (2) generally slower rates of fire spread in the chip plots; (3) modeling predictions of lower flammability in the chip plots; (4) fewer, and lesser, 1000-h fuels smoking in the chip plots on the mornings after the fires (Achtemeier et al., 2006; Glitzenstein et al., 2006), and; (5) substantial sections of the chip plots that would not burn. Regarding whether smoke results are due to less fuel being combusted, Glitzenstein et al. (2006) present various data suggesting this is likely to be the case (Glitzenstein et al., 2006). These results include (1) less area and percent area burned, (2) lower crown scorch heights indicative of lower flame heights, and (3) BehavePlus model predictions indicating lower total heat released after burns in chipped fuels (Glitzenstein et al., 2006). This last may be most convincing since total heat release is a direct function of amount of fuel consumed. We did not re-sample the fuels post-burns, so we do not know for a fact whether or not less fuel was consumed in the chip plot burns. However, the various data and model results tend to suggest that this was likely the case. Nevertheless, even if we were able to measure total fuel consumption, this still would not entirely explain the smoke results reported herein inasmuch as smoke is a function also of efficiency of combustion.

As discussed in Achtemeier and Naeher (2005), in addition to possible treatment and plot effects, the smoke differences observed in this study between the chipped vs. non-chipped plots may be explained in part by wind speed changes on the night of the burn (Achtemeier et al., 2006). The control plot was lit during a period of steady west-northwest winds lasting from 1800 to 1900 EST. These winds blew smoke directly across the ground layer sensors, especially those sensors located on the eastern side of the plot. By the time the chip plot was lit around 1930 EST, these winds had decreased. As light winds prevailed during the burning of the chipped plot, it is likely that a thermal plume developed quickly and lofted smoke above the ground sensors. Thus, the pole sensors detected most of the smoke particles in the chipped plot. Consistent with this possibility, the ratio of perimeter to pole-mounted concentrations for Plot 6 was only 0.43 as compared to a ratio of 0.67 for Plot 1 (Figures 2 and 3) (Achtemeier et al., 2006). These observations suggest that the observed differences in $PM_{2.5}$ levels among the pole mounted sensors may be the more reliable indicator of a possible chip treatment effect. If this is the case, the amount of $PM_{2.5}$ reduction due to chipping is approximately 40%, a substantial reduction but not sufficient to entirely alleviate the health risks discussed above for populations (occupational or other) immediately proximate to the fires.

The results presented herein are limited in that they are based on a single experiment in one forest in South Carolina. Nevertheless, the current study is the first attempt to collect data of this nature in an experimental context and provides an initial outcome and hypothesis that could be tested in a larger study. As such it is valuable even if not conclusive. Further, the current study was nested within a fuel and fire behavior study that was replicated, with random treatment assignment, and subject to statistical testing of treatment effects (Glitzenstein et al., 2006). The results of that study are therefore somewhat more robust with respect to general conclusions. Furthermore, the results of that study tend to support, or at least explain, the outcome observed in the smoke exposure study Glitzenstein et al., 2006.

The current study was carried out in long-unburned fuels. Consequently fuel loading, and presumably fuel consumption and smoke production, in the non-chipped plot was much higher than would be expected for a single fire in a site with a history of frequent prescribed burning Glitzenstein et al., 1995, 2003. Light fuels in which grasses predominate usually characterize such sites. Not only are total fuel loads much lower, but the light fuels are likely to be more thoroughly combusted resulting in reduced smoke production (Ottmar et al., 2001). It is therefore important to emphasize that the public health benefits of chipping are likely to be most pronounced when this treatment is utilized, as in the present situation, as a pretreatment prior to reinitiating a program of frequent prescribed fire. In any case, further experimentation is needed before we feel confident in advocating the use of chipping in other regions or for other management scenarios.

Conclusion

From the perspective of occupational and community exposures to $PM_{2.5}$ and CO, smoke exposures resulting from burned chipped plots are considerably lower than from burned non-chipped plots, at least under the conditions presented by this study. The substantial reduction in smoke on the chipped vs. non-chipped plot observed in this study potentially has important implications for both firefighters working prescribed burnings at these sites, as well as nearby communities which may be impacted from smoke traveling downwind from these sites. Public health and other benefits of chip treatments are likely to be particularly evident when this treatment is utilized to reduce or restructure heavy fuels accumulated after long periods without fires.

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