Measurements of Smoke from Chipped and Unchipped Plots

Gary L. Achtemeier
USDA Forest Service
320 Green Street
Athens, GA, 30602
706-559-4239
706-559-437 (FAX)
gachtemeier@fs.fed.us

Jeff Glitzenstein
Tall Timbers Research Station
13093 Henry Beadel Drive
Tallahassee, 32312, USA
and

Luke P. Naeher
Department of Environmental Health Science
College of Public Health
University of Georgia
Athens, GA

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Abstract

Smoke data were collected from two instrumented 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. Particulate matter ($PM_{2.5}$) data analyzed by gravimetric methods were collected at nine locations on the downwind sides of each plot. In addition, samplers were hung atop ~30 foot poles at 4 interior positions within each plot. Perimeter 12-hr $PM_{2.5}$ concentrations in the burn-only plot were significantly higher than those at the chip-burn plot. Similarly, interior 8-hr $PM_{2.5}$ concentrations in the burn-only plot were moderately higher than those at the chip-burn plot.

When possible cross-contamination was detected at a check site midway between the two plots, we used PB-Piedmont, a smoke model for predicting ground-level smoke movement at night. The modeled smoke, verified by smoke observed at the check site, indicated winds blowing 75 degrees off from winds observed at the Charleston Airport, about 50 km southwest from the experimental site.

Key words: smoke modeling, $PM_{2.5,}$ prescribed fire, carbon monoxide, particulate matter

Introduction

Southern land managers use prescribed fire to treat 2–3 million ha of forest and agricultural lands in the southern states each year (Wade et al. 2000), more than any other comparable area in the United States. In addition, the South is experiencing rapid

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population growth. Large urban centers such as Atlanta and Charlotte have grown into historically forested areas. Many people are retiring to communities located adjacent to forested areas. These demographics have created an enormous wildland/urban interface problem for Southern land managers.

Although dwelling-destroying wildfires are a threat along the wildland/urban interface, the greatest threat is from smoke – either as a nuisance (Achtemeier 2001) or as pollution (Achtemeier et al. 1998). The outcome is that many land managers have curtailed the use of fire or have abandoned fire altogether because of the threat of litigation (Mobley 1989) and have switched to more expensive mechanical methods to reduce competing midstory tree and shrub species. Furthermore, the U.S. Environmental Protection Agency has implemented more stringent regulations regarding emissions of particulate matter (EPA 2003). Wood smoke is a major source of $PM_{2.5}$ particulate matter (aerodynamic diameter of equal to or less than 2.5 microns.)

The Francis Marion National Forest (FMNF) near Charleston, South Carolina, was devastated in September 1989 when approximately one hundred million board feet of timber were felled by Hurricane Hugo (Sheffield and Thompson 1992). The outcome was a forest floor littered with logs. It was estimated that it would take 10-20 years for these 1000-hr fuels to decay into soil. Thousand hour fuels, once ignited, can smolder for days. Thus, burn plans that must take into consideration wind direction to avoid sensitive targets can be placed into jeopardy by smoke from these fuels. Wind shifts days after a prescribed burn has been completed can transport residual smoke over sensitive targets.

Because of the fallen log problem, prescribed burning was halted over large areas of the FMNF**.** One consequence was the development since Hugo of dense loblolly pine and hardwood midstories in formerly open pine woodlands and savannas. Mechanical chipping is now being utilized on these sites to remove the undesirable midstory and restore the desired ecological and burning conditions. An additional important goal is to reduce heavy fuels that pose fire and smoke hazards, including the aforementioned 1000-hr fuels.

Although mechanical chipping may reduce wildfire threats, there remains the question regarding smoke production when future prescribed fires are passed over chipped sites. Chipped materials may form moist wooden mats that could smoke profusely during the smoldering phase of prescribed burns, perhaps producing more smoke than does untreated land when subjected to fire.

Materials and Methods.

This study tested whether a plot subjected to mechanical chipping produced more $PM_{2.5}$ particulate mass during prescribed fire than a plot subjected to prescribed fire only. Because of the expense of smoke monitoring equipment, this experiment was limited to a single pair of plots. However, the two plots had the same size (1 ha) with dimensions (100 m x 100 m) and were similar with respect to pre-treatment fuels and environment. From companion studies, the number and type of smoke measuring instruments was sufficient to gain accurate measurements of total smoke production (Naeher et al. 2006) and robust data on fuels and fire behavior (Glitzenstein et al. 2006).

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Our hypothesis was that smoke production from a prescribed burn, measured by $PM_{2.5}$, would be lower in the chip-burn vs the burn-only plot. To test our hypothesis, we used a simple one tail student t-test to compare the time-integrated $PM_{2.5}$ levels measured along on the perimeter (ground level) and interior (elevated to 9m) from the chip-burn vs the burn-only plot. In addition, we compared real-time perimeter $PM_{2.5}$ in the chip-burn vs the burn-only plot.

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a) Study Site

The study was located in compartment 53 of the FMNF, in the outer south Atlantic Coastal Plain, approximately 50 km northwest of Charleston, SC (Figure 1). The site is located in the northwestern part of the FMNF within the wildland-urban interface zone surrounding the town of Moncks Corner, approximately *7* km distant. Establishment dates of midstory stems removed during the chip operation suggest that the last prescribed fire occurred shortly before the hurricane, probably during the period 1985-1988. Typical of such sites, vegetation was loblolly pine (*Pinus taeda L.)* flatwoods with dense post-Hugo regeneration dominating the mid-canopy and understory strata. In addition to loblolly pine, tree and shrub species included *Acer rubrum L., Clethra alnifolia L. , Ilex glabra (L.) Gray, Liquidambar styraciflua L., Quercus nigra L., Quercus phellos L., and Vaccinium spp.* A few open, grass patches (*Schizachyrium scoparium (Michx.) Nash)* dominated wetter micro-sites. Soils in the stand are Wahee series (Long et al. 1980) currently classified as fine, mixed, semiactive, thermic, Aeric, Endoaquult (USDA 2004). These soils are characterized by sandy loam surface soils and shallow clay subsoils (Long et al. 1980). During wet periods precipitation percolates through the surface sand and "perches" on top of the clay subsoil. Perched water tables can persist during most of the dormant season during typical winters on flat, poorly drained outer Coastal Plain sites (Long et al. 1980). An important consequence of this hydrological pattern for smoke and fire propagation is that lower litter layers and heavy fuels in contact with the soil maintain persistently high moisture levels during much of the prescribed burn season. Traditionally, most prescribed burns in the southeastern USA are carried out in winter through early spring, i.e. January through early March (Robbins and Myers 1992).

b) Experimental Design

The study site was located near enough to the coast so that land breeze circulations might extend inland far enough to impact early morning winds over the experimental sites. We therefore determined that the smoke experiment would be conducted when steady winds were from the northwest. To minimize the possibility of cross-contamination, the experimental plots were oriented along a northeast-southwest axis (Figure 2) and were separated by 300 m.

For this arrangement of instruments shown in Figure 2 to be successful, steady northwest winds were required for a minimum of 24 hours (preferably 36 hours) – the day of the burn, through the night after the burn, and into the morning of the following day. These conditions were predicted for the 36 hours beginning 12 February 2003. A cold front had passed through on 10 February, producing enough rain that one day was required to dry fuels sufficiently for a satisfactory burn. However, a dry secondary cold front passed through on 12 February and northwesterly winds persisted through the next

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morning. Thus, February 12-13 was a suitable window of opportunity for the smoke experiment during winter-spring 2003.

c) Instrumentation for Smoke Data

Particulate data analyzed by gravimetric methods were collected by SKC pumps drawing air at a rate of 4.0 L/min through a BGI KTL cyclone and SKC Air Check 2000 pumps drawing air at a rate of 1.5 L/min through a BGI Triplex cyclone (Naeher et al. 2006). Both cyclone types used 37 mm Teflo filters to which the particles adhered. A line of SKC Air Check 2000 pumps was positioned along the downwind side and part way up the adjacent sides of each plot (Figure 2). Pumps were separated by approximately 20 m and the cyclones were hung approximately 1.5 m off the ground. In addition to the ground level samplers, SKC pumps were hung atop 9 m poles at four positions within the interior of each smoke monitoring plot. Pumps were set to run throughout the night (6pm-6am) 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, $PM_{2.5}$ samples were collected, put in boxes, sealed, and refrigerated. They were later brought back from FMNF to a partially climate-controlled room for analysis in the Department of Environmental Health Science, University of Georgia (Naeher et al. 2006).

Real time aerosol $PM_{2.5}$ data were collected by TSI Dust Trak monitors that used laser photometry to record airborne dust concentrations. Drager PAC III and Langan instruments were used for real time CO data collection (Naeher et al. 2006). A Langan

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CO monitor and a TSI Dust Trak were positioned along the downwind sides in both plots (Figure 2). PAC IIIs were placed at the downwind corners of the plots.

A SKC Air Check pump was co-located with a weather station in the open space midway (i.e. 150 m) between the two plots. The purpose for the control sampler was to monitor for cross-contamination between the two plots. The weather station was a Campbell Scientific CR23X Station. Wind and air sensor heights were approximately 3.5 m above ground. Sensor data were taken and stored every 10 seconds. The sensor for air temperature (C) and relative humidity (RH) was a Vaisala Inc. HMP45C with temperature accuracy +/- 0.2 C at 20 Degrees and RH accuracy 2 percent from 0-90 percent RH and 3 percent from 90-100 percent RH. Wind speed ($m\ s^{-1}$) and direction measurements were taken via a RM Young Inc. wind monitor. Wind speed accuracy is +/- 2 percent; wind speed threshold is 0.9 $m\ s^{-1}$. Wind direction accuracy is approximately +/- 5 percent.

Results

a) Smoke observations

Low relative humidities and strong winds during the day of 12 February 2003 delayed ignition on the two experimental plots until after sunset (5:57PM). The burn-only plot was ignited at 6:15PM and the chipped-burn plot was ignited at 7:30PM. Given the potential hazard of lighting strips in the dark in dense vegetation, the firing technique for the burn-only plot was to ignite a backfire on the downwind side, allow it to burn out a broad “blackline” about 20 m wide, and then to ignite the upwind side of the plot. The

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Fuel data were collected from the chip-burn and burn-only study plots prior to the experimental fires. Information of methods for collecting fuels data can be found in Glitzenstein et al. (2006). Briefly, data on downed woody fuels were collected using Brown’s vertical plane method (1974, 1982). Fifteen-meter long transects were located at eight systematic locations in each plot.

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fire front moved rapidly across the plot, covering the 80 meter or so distance to the blackline in less than 10 minutes, i.e., an estimated rate of spread of approximately 7.8 m min^{-1}. Flame lengths appeared to be mostly less than 1.0 m, but with occasional flare ups up to 5.0 m as pyrogenic shrubs, e.g., *Myrica cerifera*, were combusted. In contrast, the fire moved slowly through the chipped-burn plot, necessitating numerous strip headfires in order to ultimately burn the majority of the plot area. Flame lengths were also much lower, averaging approximately 25 cm according to field observations.

$PM_{2.5}$ total mass measurements for the two plots are shown in Figures 3 and 4. Smoke particulate concentrations in the burn-only plot exceeded those at the chipped-burn plot at each of the 4 pole-mounted and at 8 of the 9 ground locations.

A more detailed temporal picture of $PM_{2.5}$ emissions at ground level in the burn-only plot was provided by the TSI Dust Trak located at position 1-5 on the downwind side of the plot (Figure 3). From Figure 5, the instrument was turned on at 3:00PM and turned off 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} (milligrams per cubic meter) during this period. Concentrations remained high during the active flaming stage of the burn, then fell to less than 2 mg m^{-3} after 6:30PM and then to near background levels by 7:30PM. Concentrations increased to 5-10 mg m^{-3} after 7:30PM.

The record for the chipped-burn plot (blue line) began with a sharp peak in smoke concentrations to 9 mg m^{-3} at 7:30PM then dropped off to near background levels until after 8:30PM when smoke concentrations peaked between 2-3 mg m^{-3}.

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Perimeter 12-hr $PM_{2.5}$ concentrations in the burn-only plot (AVG 519.9 µg m^{-3}, STDEV 238.8 µg m^{-3}) were significantly higher (t Stat 2.96, one tail p-value 0.01) than those at the chipped-burn plot (AVG 198.1 µg m^{-3}, STDEV 71.6 µg m^{-3}). Similarly, interior pole-mounted 8-hr $PM_{2.5}$ concentrations in the burn-only plot (AVG 773.4 µg m^{-3}, STDEV 321.8 µg m^{-3}) were moderately higher (t Stat 2.18, one tail p-value 0.06) than those at the chipped-burn plot (AVG 460.3 µg m^{-3}, STDEV 147.3 µg m^{-3}).

b) Analysis for Cross-Contamination

An important issue concerns possible contamination between smoke monitoring plots. The plots were oriented along a southwest/northeast axis based on the expectation that steady winds from the northwest would avoid cross-contamination. A TSI Dust Trak $PM_{2.5}$ sampler and a Langan CO monitor were collocated with the weather station at a check site located half way between the burn-only and the chipped-burn plots (Figure 2) to monitor for cross contamination. The total $PM_{2.5}$ mass concentration measured at the check site was 178.5 ug m^{-3}. Figure 5 shows the trace for the Dust Trak (green line). Contamination began at 9:00PM, approximately 1.5 hours after ignition and probably during the smoldering phase at the chipped-burn plot. The concentrations are small in comparison with post-burn smoldering $PM_{2.5}$ measurements at the burn-only site but are typical of $PM_{2.5}$ measurements at the chipped-burn site.

Hourly wind reports at the Charleston, SC, airport, approximately 50 km southwest of the experiment site, showed that the wind directions ranged from 270 degrees (wind blowing from the west) to 310 degrees (wind blowing from the west-

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northwest) through the period from 5:00PM on 12 February to 7:00AM on 13 February. Given the arrangement of the plots along a northeast-southwest axis, these wind directions did not support smoke from the chipped-burn plot passing over either the check site or the burn-only plot. A critical wind direction of 232 degrees (wind blowing from the southwest) would be required for smoke from the extreme northwest corner of chipped-burn plot to just pass over the check site.

Wind directions more representative of below canopy air movement over the experiment site were collected from the weather station at the check site. During the period from 6:00 – 6:30PM, as wind speeds were decreasing (Figure 6), winds blew from the west (273-279 degrees). After 6:30PM, wind speeds fell below the recording threshold for the instrument. However, the wind direction vane was still responding to the winds until 7:30PM. Wind directions ranged from 258 degrees (winds blowing from the west-southwest) to 298 degrees (winds blowing from the west-northwest) with the west-southwest winds appearing later in the hour. After 7:30PM, wind directions became unreliable; there were longer periods with wind speeds below the response of the vane. Wind directions from 7:30-7:50PM ranged from 277 degrees to 306 degrees (winds blowing from the west to west-northwest). Analysis of wind directions stopped after 7:50PM. Thus reliable wind direction data ceased only 20 minutes after ignition at the burn-only plot and more than an hour before cross contamination was detected at the control site.

DISCUSSION

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From Figures 3 and 4, smoke particulate concentrations in the burn-only plot exceeded those at the chipped-burn plot at the 4 pole-mounted locations and at 8 of the 9 ground-mounted locations. The difference was especially pronounced for the ground level sensors. In addition to possible treatment and fuel differences, this large difference may be explained by wind speed changes on the night of the burn. The burn-only plot was lit during a period of steady west-northwest winds lasting from 6:00-7:00PM. These winds blew smoke directly across the ground-level sensors. By the time the chipped-burn plot was ignited around 7:30PM these winds had dissipated. Since light winds prevailed, 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 from the chipped-burn plot. Consistent with this possibility, the ratio of perimeter to pole-mounted concentrations for the chipped-burn plot (excluding position 6-6 as an outlier) was only 0.47 as compared to a ratio of 0.91 for burn-only plot.

We suggest that development of a thermal plume above each burn is supported by the time series measurements from the TSI Dust Trak (Figure 5). Stronger winds (Figure 6) during the active flaming phase at the burn-only plot blew smoke along the ground from 6:00-6:30 PM and over the Dust Trak resulting in high measured smoke concentrations. After 6:30PM, the light winds made it possible for residual flames plus heat from the ground to develop a thermal plume with sufficient organization to loft smoke above the smoke collectors located on the burn-only plot boundaries. After 7:30PM, the ground had cooled sufficiently so that a thermal plume was no longer supported. This, in combination with an intensifying nocturnal inversion, trapped smoke

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near the ground with the resulting second increase in $PM_{2.5}$ concentrations measured by the Dust Trak after 7:30PM.

The time series for $PM_{2.5}$ as measured by the TSI Dust Trak at Position 5 within the chipped-burn plot is shown by the blue line in Figure 5. $PM_{2.5}$ concentrations observed by this instrument were uniformly lower than those observed by the Dust-Trak at the burn-only plot over the same time period (red line). The chipped-burn trace indicated an initial spike in concentrations when the back fire line was lit near the instrument. However, the magnitude of the spike was much smaller than that observed for the burn-only plot. The concentration minimum at chipped-burn plot that followed the initial spike was also much less pronounced than that for the burn-only plot. Thus, the fine scale temporal record of $PM_{2.5}$ emissions provided by the chipped-burn plot Dust-Trak supported the inference from the mass samplers that a thermal plume developed relatively rapidly in this fire and lofted most of the smoke above the ground samplers. As there was no abrupt ending of the active flaming phase, the thermal plume in the chipped-burn plot appears to have gradually weakened within an increasingly strong nocturnal inversion. Thus, the $PM_{2.5}$ record became more continuous after 9:00PM.

Regarding cross contamination, Achtemeier (2005) developed PB-Piedmont, a numerical wind model specifically designed to simulate smoke movement in very light winds near the ground at night. The model uses gradients of the pressure field calculated from seven to ten National Weather Service ground stations surrounding a burn site to mathematically simulate air movement under light wind situations. This approach avoids reliance on inaccurate wind reports from ground weather stations at night. Although designed to be used in terrain typical of that of the Piedmont of the South, we determined

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the model could be used to investigate the source of the cross contamination because land cover was relatively uniform (detailed land use data were unnecessary), road cuts that would channel the wind were located east and south of the site (downwind from the burns), and the weather patterns remained well-organized through the night

PB-Piedmont was initialized with USGS 30-m DEM elevation data and hourly weather data from National Weather Service surface weather reporting stations for the period from 5:00PM 12 February to 6:00AM 13 February. The model burn was started at 7:30PM. Figure 7a shows both plots (red squares rotated 45 degrees) and the check site (green circle) geo-referenced to elevation. Colored bands represent one meter; the elevation range is seven meters over this roughly 500 m square grid. PB-Piedmont assumes a burn site can be represented by a square. This square (white) is collocated with the chipped-burn plot. As locations of smoldering fuels within chipped-burn plot were unknown, a 25-point matrix was overlain on the white square in the model. PB-Piedmont simulated smoke movement from each point within the matrix.

The timing of smoke arrival at the check site in the PB-Piedmont simulation can be compared with the TSI Dust Trak $PM_{2.5}$ concentrations (green line in Figure 5). The smoke plume at 8:00PM (Figure 7b), one hour before smoke was detected by the Dust Trak, was blowing at the critical wind direction of 232 degrees (blowing from the southwest). By 10:00PM, the time of the peak in $PM_{2.5}$ concentrations measured by the check site Dust Trak, the winds had shifted to blow from 229 degrees thus enveloping the check site with smoke (Figure 7c) and impacting the eastern edge of Plot 1. The smoke plume remained over the check site and the burn-only plot (Figure 7d and 7e) through the night until 6:00AM 13 February when the wind direction was blowing from the critical

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direction again. The Dust Trak stopped reporting smoke at 6:00AM. Smoke again returned to the check site after 7:00AM.

MANAGEMENT IMPLICATIONS

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1. The active burn phase smoke production in the chipped-burn plot was about 60% of that in the burn-only plot as observed from the pole-mounted sensors. Given the overall reduction in smoke from the chipped-burn plot, mechanical chipping may be a useful method for reducing mid-story fuels buildup along smoke-sensitive wildland/urban interfaces in Southern forests.
2. If these results are extrapolated to an operational scale burn, it is clear that fairly high levels of smoke would still be produced in both active burn and smoldering phases. This much smoke could still necessitate follow-up expenses in terms of traffic control and interventions with local residents with medical conditions.

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4. An important and somewhat unexpected result to emerge from this study was an appreciation for how difficult it is to predict where smoke will be transported at night even for well-defined synoptic weather conditions and flat terrain. Despite forecasted strong winds out of the northwest, actual wind directions and smoke movements on the night of the smoke burn were quite different from that expected.
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Figure Captions

Figure 1. Location of the experimental burn site (black dot) within the Francis Marion National Forest (highlighted in dark gray) within South Carolina.

Figure 2. Distribution of ground and tower samplers and the weather station for the FMNF smoke measuring experiment. The distance (300 m) between the burn-only and chipped-burn plots is not to scale.

Figure 3. Plan view of the burn-only plot showing magnitudes and distributions of $PM_{2.5}$ particulate mass ($\mu g/m^3$) for the pole-mounted and ground-level samplers.

Figure 4. Plan view of the chipped-burn plot showing magnitudes and distributions of $PM_{2.5}$ particulate mass ($\mu g/m^3$) for the pole-mounted and ground-level samplers.

Figure 5. Concentrations of $PM_{2.5}$ (mg/m^3) from a TSI Dust Trak at burn-only position 1-5 (Figure 3) (red), chipped-burn position 6-5 (Figure 4) (blue), and check site (green) with vertical scale from 0-15 mg/m^3.

Figure 6. The 15-min average wind speed from 6:00-11:00PM 12 February 2003 as measured from the weather station located at the control site.

Figure 7. PB-Piedmont smoke model simulation of the ground-level smoke plume from the chipped-burn plot on 12 February 2003 for a) initial graphic, b) 8:00PM, c) 10:00PM, and on 13 February for d) 1:00AM, e) 4:00AM, and f) 6:00AM.

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MANAGEMENT IMPLICATIONS¶

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PB-Piedmont simulated smoke ... [14]

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1000-hr fuels were recorded across the entire transect length. In addition, fine fuels, including 1-hr and 10-hr downed woody fuels, were collected along each transect from a 0.25 m^2 randomly located circular plot. Harvested fuels were sorted into standing grass-plus-forbs, live woody plants, standing dead woody plants, fine litter and the two twig components (in the chip plots this included fragments generated by the chipping operation). In addition, percentages of fine litter were visually estimated for pine litter, hardwood litter, and non-standing grass-plus-forbs. Depth of duff was determined at the center point of each 0.25 m^2 plot after the litter was harvested. The different standing and litter fuel components were bagged, dried at 60 degrees C and weighed. "Grab samples" of the primary litter components were collected from burn-plots prior to lighting the fires. Wet weight was determined in the field; samples were then bagged and, subsequently, dried and weighed.

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Not all SJAF readers will be familiar with burning jargon. Please rephrase this to clarify the meaning, e.g., " was to ignite a back fire on the down wind side and allow it to back off the line approximately xx m before igniting the upwind side of the plot

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Low relative humidities and strong winds during the day of 12 February 2003 delayed ignition on the two experimental plots until after dark (state the time of ignition here). Given the potential hazard of lighting strips in the dark in dense vegetation the firing technique for the burn-only plot was to install a broad black-line on the downwind side and then to ignite the upwind side of the plot. The fire front moved rapidly across the plot, covering the 80 meter or so distance between backline and blackline in less than 10 minutes, i.e., an estimated rate of spread of approximately 7.8 m min^{-1}. Flame lengths appeared to be mostly less than 1 m, but with occasional flare ups up to 5.0 m as pyrogenic shrubs, e.g., *Myrica cerifera*, were combusted. In contrast, the fire moved

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slowly through the chipped plot, necessitating numerous strip headfires in order to ultimately burn the majority of the plot area. Flame lengths were also much lower, averaging approximately 25 cm according to field observations.

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An important issue concerns possible contamination between smoke monitoring plots. The plots were oriented along a southwest/northeast axis based on the expectation that consistent winds from the northwest would avoid cross-contamination. A TSI Dust Trak $PM_{2.5}$ sampler and a Langan CO monitor were collocated with the weather station at a check site located half way between the two plots

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, approximately 1.5 hours after ignition and probably during the smoldering phase at

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the chip-burn plot. The concentrations are small in comparison with post-burn smoldering $PM_{2.5}$ measurements at the burn-only

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(Figure 2) to monitor for cross contamination. The total $PM_{2.5}$ mass concentration measured at the check site was 178.5 ug m^{-3}. Figure 5 shows the trace for the Dust Trak (green line). Contamination began at

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but are typical of $PM_{2.5}$ measurements at the chip-burn

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, the ground had cooled sufficiently so that a thermal plume was no longer supported. This, in combination with an intensifying nocturnal inversion, trapped smoke near the ground with the resulting second increase in $PM_{2.5}$ concentrations measured by the Dust Trak after 1930 LST.

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The time series for $PM_{2.5}$ as measured by the TSI Dust Trak at Position 5 within

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th chip-burn plot is shown by the blue line in Figure 5. $PM_{2.5}$ concentrations observed by this instrument were uniformly lower than those observed by the plot 1 Dust-Trak over the same time period (red line). As in

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chip-burn plot trace indicated an initial spike in concentrations when the back fire line was lit near the instrument. However, the magnitude of the spike was much smaller than that observed for the Plot 1 burn. The concentration minimum at Plot 6 that followed the initial spike was also much less pronounced than that for the Plot 1 burn. Thus, the fine scale temporal record of $PM_{2.5}$ emissions provided by the Plot 6 Dust-Trak supported the inference from the mass samplers that a thermal plume developed relatively rapidly in this fire and lofted most of the smoke above the ground samplers. As there was no abrupt ending of the active flaming phase, the thermal plume in Plot 6 appears to have gradually weakened within an increasingly strong nocturnal inversion. Thus, the $PM_{2.5}$ record became more continuous after

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(See previous fax for formatting corrections and SJAF Citation instructions available on line for additional clarifications.)

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