

**BLACK CARBON IN DOWNWIND AREA PM<sub>2.5</sub> SAMPLES COLLECTED DURING  
PRESCRIBED BURNS IN SOUTHEASTERN US FORESTS**

by

MICHAEL O'BRIEN

(Under the Direction of Luke P. Naeher)

**ABSTRACT**

**Introduction:** Woodsmoke produces various pollutants, such as PM<sub>2.5</sub> (Particulate Matter 2.5) and Black Carbon (BC).

**Methods:** Filters from two Southeastern US Forests were analyzed for BC.

**Results:** For the SRS study, BC and BC/PM<sub>2.5</sub> levels were determined. Mixed effects models were used to determine relationships between BC, PM<sub>2.5</sub>, and the BC/PM<sub>2.5</sub> ratio with distance and wind hits. Both BC and PM<sub>2.5</sub> decreased significantly with increasing distance, and increased significantly with increased wind hits. For the BC/PM<sub>2.5</sub> Ratio, this was not seen for either effect. For the Francis Marion study, BC and BC/PM<sub>2.5</sub> levels were determined for both a mechanically chipped and an unchipped plot.

**Discussion and Conclusion:** Overall, this data adds to BC literature and is novel in that it also helps add to the understanding of the spatiotemporal dynamics of BC during a prescribed burn.

**INDEX WORDS:** Particulate Matter, PM<sub>2.5</sub>, Black Carbon, BC, SootScan, Prescribed Burns

**DOWNWIND EXPOSURE TO BLACK CARBON MEASURED ON PM<sub>2.5</sub> FILTERS  
FROM PRESCRIBED BURNS AT SAVANNAH RIVER SITE**

by

MICHAEL O'BRIEN

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MICHAEL O'BRIEN

Major Professor: Luke P. Naeher  
Committee: Olorunfemi Adetona  
Robert Gogal  
Travis Glenn  
Stephen Rathbun

Electronic Version Approved:

Ron Walcott  
Dean of the Graduate School  
The University of Georgia  
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## **CHAPTER 1**

### **INTRODUCTION & LITERATURE REVIEW**

#### **Overview**

In recent years, the prevalence of forest fires have been increasing, particularly in the Western United States, due in part to anthropogenic climate change (Juang et al. 2022). Increased fires in the United States leads to the potential problem of downwind exposures of different pollutants like Black Carbon (BC) among the general public. Communication of the risk of exposure to BC as well as other pollutants would be important in interactions with the public during fires in the future.

#### **Black Carbon Background**

Black Carbon (BC) is a component of the pollutant PM<sub>2.5</sub> that is formed through incomplete combustion of fossil fuels as well as during the burning of wood in wildland fires (Coppola et al. 2022). With regards to specific health outcomes, BC has been linked to various detrimental health effects such as premature mortality (Wang et al. 2021) and cardiovascular disease (Song et al. 2022), and has been implicated in Climate Change (Harmsen et al. 2020). Animal studies in mice have shown that exposure negatively impacts the male reproductive system (Jiang S. et al. 2023), and increases the expression of inflammatory cytokines and chemokines in lung tissue (Chu et al. 2018). In vitro studies have also revealed that it can affect the viability of human bronchial cells (Ge et al. 2021) and can also induce mitochondrial dysfunction (Shang et al. 2022). It is an occupational exposure among wildland firefighters

during prescribed burns, as has been demonstrated in past studies (Wu et al. 2021, Adetona et al. 2022).

It should also be noted that BC is technically a heterogenous mixture of different substances, which includes Elemental Carbon, Polycyclic Aromatic Hydrocarbons, heteroatoms like Oxygen and Nitrogen, as well as other trace elements which can vary (Long et al. 2013). Variations in the relative share of these various constituents in BC could potentially lead to differences in effects.

### **Personal Black Carbon Exposure Studies**

There have been several studies done on Personal Black Carbon (BC) exposures from vegetative smoke, most of them related to occupational exposures among firefighters. For example, Allen et al. (2008) looked at changes in airway inflammation and lung function among nineteen children (Ages 6-13) with asthma in woodsmoke-impacted areas of Seattle from December 2000 to May 2001. They measured 24 hour outdoor and personal concentrations of PM<sub>2.5</sub> and Light-Absorbing Carbon (LAC), a surrogate for Black Carbon. Personal PM<sub>2.5</sub> levels were measured on all study participants using Harvard personal environmental monitors (HPEM, Harvard School of Public Health, Boston). The authors found that the personal PM<sub>2.5</sub> mean was 12.73  $\mu\text{g}/\text{m}^3$  and the range was 1.04-45.19  $\mu\text{g}/\text{m}^3$ . The personal LAC mean was 1.27  $\mu\text{g}/\text{m}^3$  and the range was 1.17-6.25  $\mu\text{g}/\text{m}^3$ .

Adetona et al. (2017) looked at personal exposure to PM<sub>2.5</sub> by looking at personal gravimetric PM<sub>2.5</sub> samples in the breathing zone of wildland firefighters during their workshifts using MicroPEMs equipped with Teflon filters. PM<sub>2.5</sub> on sample filters were analyzed for LAC as a surrogate for Black Carbon. The subjects were 10 firefighters and 2 volunteers at the

Savannah River Site (SRS). They were monitored from January to July 2015. The authors looked at PM<sub>2.5</sub> and BC levels by work tasks performed by the firefighters, and found that the geometric mean for gravimetric PM<sub>2.5</sub> samples taken from firefighters performing holding was 338 µg/m<sup>3</sup> (95% CI, 174, 654), while it was 240 µg/m<sup>3</sup> (95% CI, 134, 430) for lighting. The mean for absorption coefficients for lighting was 60.7 10<sup>-5</sup>m<sup>-1</sup> (95% CI, 34.5, 107), while it was 22.3 10<sup>-5</sup>m<sup>-1</sup> (95% CI, 11.6, 43.1) for holding. This study is a subset of a larger exposure study. The complete exposure set was published in work done by Adetona et al. in 2022.

Another study by Adetona et al. (2019) looked at BC exposure among 10 firefighters and 2 volunteers at the Savannah River Site (using LAC as a surrogate for Black Carbon). Samples were collected from January-July 2015. The authors used MicroPEM instruments with Teflon filters in order to assess the exposure to PM<sub>2.5</sub> and BC in the breathing zone of the subjects on burn and non-burn work days. They found that average PM<sub>2.5</sub> concentrations were 35.1 µg/m<sup>3</sup> (95% CI, 15.9, 77.3) on non-burn work days, and 259.4 µg/m<sup>3</sup> (95% CI, 156.1, 431.1) on burn days. The authors used LAC as a surrogate for Black Carbon, and the overall absorption coefficient for burn days was 46.5 x 10<sup>-5</sup>m<sup>-1</sup> (95% CI, 33.0, 65.5) and 0.8 x 10<sup>-5</sup>m<sup>-1</sup> (95% CI, 0.5, 1.1) for non-burn days. This study is a subset of a larger exposure study. The complete exposure set was published in work done by Adetona et al. in 2022.

Work by Wu et al. (2021) observed Personal PM<sub>2.5</sub> and BC exposure among 35 firefighters doing prescribed burns in the Midwest of the United States. The samples were taken in March and April 2020. They used MicroPEM instruments with Teflon filters in order to assess this. They found that the geometric mean of PM<sub>2.5</sub> exposure was 1.75 ± 1.20 mg/m<sup>3</sup>, while the

range of PM<sub>2.5</sub> exposure was 0.35-5.25 mg/m<sup>3</sup>. The geometric mean of BC exposure was 72.29 ± 48.79 µg/m<sup>3</sup>, while the range of BC exposure was 7.35-250.16 µg/m<sup>3</sup>.

Another study by Wu et al. (2021) looked at personal exposure to Black Carbon among 38 wildland firefighters doing a prescribed burn. The firefighters were from both the United States Department of Agriculture-Wayne National Forest (WNF) and Ohio Department of Natural Resources-Division of Forestry (ODNR-DF). They accomplished this by using MicroPEM (equipped with Teflon filters) in the breathing zone of the wildland firefighters during prescribed burns. They found that on burn days the mean PM<sub>2.5</sub> concentration was 1.43 ± 0.13 mg/m<sup>3</sup> and the mean BC concentration was 58.79 ± 5.46 µg/m<sup>3</sup>. This study is a subset of a larger exposure study. The complete exposure set was published in work done by Adetona et al. in 2022.

Finally, work by Adetona et al. (2022) also looked at personal exposure to PM<sub>2.5</sub> and Black Carbon among wildland firefighters doing prescribed burns. Ten of the twelve wildland firefighters were employed by the United States Forest Service-Savannah River (USFS-SR), South Carolina, the other two were volunteers. The study looked at personal exposure to PM<sub>2.5</sub> and Black Carbon among the firefighters during their work shifts by conducting personal real-time and gravimetric PM<sub>2.5</sub> measurements in the breathing zone of the firefighters by using MicroPEM instruments equipped with Teflon filters. The filters were then measured for measurement of Light absorbing Carbon (LAC). The geometric mean of the gravimetric PM<sub>2.5</sub> levels for samples taken from burn days was 240 µg/m<sup>3</sup> (95% CI, 179, 321), while the levels for the integrated real-time samples had a geometric mean of 175 µg/m<sup>3</sup> (95% CI, 139, 221). The Overall absorption coefficient samples from burn days was 46.5 10<sup>-5</sup>m<sup>-1</sup> (95% CI, 33.0, 65.5).

For samples taken from non-burn days, the geometric mean for gravimetric PM<sub>2.5</sub> was 42 µg/m<sup>3</sup> (95% CI, 30, 60), while it was 13 µg/m<sup>3</sup> (95% CI, 9, 17) for integrated real time PM<sub>2.5</sub>. The absorption coefficient for non-burn days was 0.8 10<sup>-5</sup>m<sup>-1</sup> (0.5, 0.11).

Overall, it is clear that although there are few studies on personal exposure to BC from biomass burning, the studies that have been done have shown that the levels of BC encountered by firefighters are relatively high, compared to most of the ambient studies done, which are discussed below.

### **Downwind/Ambient Exposure Studies**

Compared to Personal Exposure studies on vegetative BC smoke exposure, there are many more on Ambient/Downwind BC smoke exposure. For example, Dutkiewicz et al. (2011) reported high concentrations of Black Carbon aerosols at two rural sites in New York (Mayville and Whiteface Mountain) in May 2010 that were linked to wildfire activity in Canada. The authors used the Magee Scientific model AE21 Aethalometer to measure BC levels at the Whiteface Mountain Site while they used the Magee Scientific model AE22 Aethalometer to measure BC levels at the Mayville Site. The AE21 and AE22 record BC concentrations at two wavelengths, 880 and 370 nm, designated BC and BC<sub>UV</sub>, respectively. BC values at the Mayville site ranged from 0-6000 ng/m<sup>3</sup> using the primary 880nm channel, while the values at Whiteface Mountain ranged from 0 to 1500 ng/m<sup>3</sup> from the primary 880nm channel. PM<sub>2.5</sub> values were not reported at the Mayville site, while they ranged from 0 to 150 µg/m<sup>3</sup> at the Whiteface Mountain site.

Work by Crabbe (2012) looked at the risk of hospitalization from bushfire exposure events in Darwin, Australia from 1993-1998. The incidence of daily counts of hospital

admissions for respiratory and cardiovascular diagnoses was calculated with respect to exposures of Particulate Matter (PM<sub>10</sub>), fine particulate matter, and black carbon composition. The PM<sub>10</sub> range was 0.52-42.5 µg/m<sup>3</sup> while the BC range was from 3.4 to 3,384 ng/m<sup>3</sup>. The authors also found that respiratory admissions to the hospital were also associated with black carbon concentrations recorded the previous day (RR=1.0004 for each 1 ng/m<sup>3</sup> increase in BC, 95% CI, 1.000-1.008, p<0.05).

Another study by Aurell and Gullett (2013) compared Aerial- and ground-sampled emissions of PM<sub>2.5</sub> and Black Carbon from three prescribed forest burns in the southeastern US to emissions from laboratory open burn tests. The three areas that were monitored were Eglin Air Force Base in Florida, Camp Lejeune in North Carolina, and Fort Jackson in South Carolina. The data was gathered in February 2011 for Eglin Air Force Base, in February and March 2011 for Camp Lejeune, and in November 2011 for Fort Jackson. The authors found that the PM<sub>2.5</sub> emission factors ranged from 14-47 g/kg biomass, and that the BC emission factors ranged from 1.2-2.1 g/kg biomass.

May et al. (2014) described a set of measurements of rBC (refractory Black Carbon) and non refractory PM in emissions from prescribed fires in the US, including aircraft measurements in young plumes from 13 prescribed burns in California and South Carolina. The California fires took place in the fall of 2009, while the South Carolina fires took place in the fall of 2011. The PM<sub>1</sub> emission factors ranged from 0.035 g/g to 0.10 g/g across all fires, while the rBC values ranged from 6.3 to 37 ng sm<sup>-3</sup> ppbv<sup>-1</sup> across all fires.

Work by Kang et al. (2014) looked at levels of PM<sub>2.5</sub> and Black Carbon in Boston during two wildfire events in Quebec, Canada. One fire was in northern Quebec in early July 2002,

while the other was in southern Quebec, late May 2010. Ambient Particulate samples were collected at the Harvard Supersite, on the library roof of the Harvard Medical School. In the 2002 fire, PM<sub>2.5</sub> levels ranged from 0 to 100  $\mu\text{g}/\text{m}^3$ , while in the 2010 fire the PM<sub>2.5</sub> levels ranged from 0 to 150  $\mu\text{g}/\text{m}^3$ . In the 2002 fire, BC levels ranged from about 0.5 to 3  $\mu\text{g}/\text{m}^3$ , and in the 2010 fire it ranged from about 0.5 to 6  $\mu\text{g}/\text{m}^3$ .

Youssouf et al. (2014) looked at wildfires that took place in Europe between 2006 and 2010 and assessed the amount of Black Carbon in tons released in those wildfires as a sum, including countries like Albania, Algeria, France, Spain, Serbia, Italy, Greece, Portugal, Croatia, and others. The sums ranged from 5.1 tons for Romania to 9267.4 tons for Portugal.

Another study by Holder et al. (2016) characterized PM and BC emissions factors for two series of prescribed fires that took place in Florida and South Carolina. Refractory Black Carbon (rBC) emission factors measured at ground level ( $\sim 2\text{m}$ ) were  $0.76 \pm 0.15$  g/kg, while it was  $0.93 \pm 0.32$  g/kg measured aloft ( $\sim 100\text{-}600\text{m}$ ). However, it was noted that PM emission factors measured by aircraft were only 18% ( $5.4 \pm 2.0$  g/kg) of those measured on the ground ( $28.8 \pm 9.8$  g/kg).

Healy et al. (2019) looked at Aethalometer data collected at six sites in the Lower Fraser Valley (LFV), British Columbia, from September 2016 through August 2017 and analyzed them to investigate the relative importance of fossil fuel and biomass burning contributions to black carbon in the region. The PM<sub>2.5</sub> range was about 0-150  $\mu\text{g}/\text{m}^3$  and the BC range was about 0-6  $\mu\text{g}/\text{m}^3$ .

Work by Selimovic et al. (2019) looked at the major wildfire smoke and haze episode that took place between mid-August and mid-September 2017 that impacted the Northwest US and

Southwest Canada. During this time the authors' ground-based site in Missoula, Montana experienced heavy smoke impacts for about 500 hours. They measured wildfire trace gasses, PM<sub>2.5</sub>, and black carbon. The authors found that the PM<sub>2.5</sub> range was about 0-471  $\mu\text{g}/\text{m}^3$  and the BC range was about 0-3.62  $\mu\text{g}/\text{m}^3$ .

Zhu et al. (2019) looked into sources of atmospheric black carbon and related carbonaceous components at Rishiri Island, Japan. They quantified daily values from April 1, 2014 to March 31, 2015 for equivalent Black Carbon (eBC) particle mass in  $\text{ng}/\text{m}^3$ . The authors found sixteen high eBC events, and specifically observed elevated eBC in July 2014, which was attributed to the forest fires in Siberia at the time. The overall range for eBC values was from 0 to about 1900  $\text{ng}/\text{m}^3$ .

Another study by Shrestha et al. (2019) continuously monitored both outdoor and indoor number concentrations of PM<sub>2.5</sub>, Black Carbon, Carbon Monoxide, and Nitrogen Dioxide for two to seven days in 28 low-income homes in Denver Colorado, during the 2016 and 2017 wildfire seasons. BC levels varied widely based on house, year, and whether the measurement was done indoors or outdoors. For example, one house in June 2017, over the course of two days, had a range of about 0-7500  $\text{ng}/\text{m}^3$  for outdoor BC and about 0-3000  $\text{ng}/\text{m}^3$  for indoor BC. They found that many indoor activities like cooking can cause periodic spikes in these pollutants, but also that outside pollutant levels lead to higher pollutant levels inside even when all barriers like windows are closed. This, they concluded, shows that homes are less powerful barriers to outdoor air pollution than previously thought.

Work by Cruz-Nunez and Estefania Bulnes-Aquino (2019) used HYSPLIT simulations, which determine trajectories of airborne pollutants, to estimate pollutant trajectories of a wildfire

in Tepozteco National Park in Morelos, Mexico in April 2016 along with a dispersion simulation to determine pollutant concentrations as a function of distance to the centers of population. The total emissions over 24 hours was 4409 kg for PM<sub>2.5</sub> and 540 kg for BC.

Castagna et al. (2021) monitored eBC and CO during an intense season of wildfires in south Italy. These were recorded at the high-altitude Global Atmosphere Watch (GAW) Monte Curcio (MCU) regional station from June 1st to September 30th of 2017. The eBC measurements ranged from 0 to 3.0  $\mu\text{g}/\text{m}^3$ .

Work by Ivancic et al. (2023) analyzed the Camp Fire's influence on air quality in Northern California by measuring highly time-resolved total carbon (TC), black carbon (BC), and organic carbon (OC) were measured using the Carbonaceous Aerosol Speciation System at a site in Berkeley, California. Daily Averaged PM<sub>2.5</sub> concentrations exceeded 200  $\mu\text{g}/\text{m}^3$  in Berkeley during this time, although this was measured by Purple Air and not by the authors of this study. This study reported median Black Carbon levels, which were 1  $\mu\text{g}/\text{m}^3$  before the fire and about 4  $\mu\text{g}/\text{m}^3$  for phases I and II of the fire.

Finally, Wei et al. (2023) tried to estimate trends in black carbon and PM<sub>2.5</sub> concentrations and their attributable mortality burden across the USA. The authors derived daily concentrations of PM<sub>2.5</sub> and black carbon at a 1-km resolution in the USA from 2000 to 2020 via deep learning, using data taken from satellites, models, and surface observations. They estimated Black Carbon-attributable mortality burden and also investigated the spatiotemporal linear-regressed trends in PM<sub>2.5</sub> and black carbon pollution and their associated premature deaths from 2000 to 2020. The PM<sub>2.5</sub> range for daily values in this study was about 0 to 700  $\mu\text{g}/\text{m}^3$  while the BC range was about 0 to 18  $\mu\text{g}/\text{m}^3$ . They also found that premature mortality

from PM<sub>2.5</sub>, with and without the added effect of BC, has been declining in tandem with decreases in these pollutants in different regions of the country.

Overall, the literature on ambient/downwind exposures of BC is much more expansive than the literature on personal exposures. The levels are also lower, which could be due to proximity to the burn compared to personal studies done. Although they are lower it is a much more common exposure scenario for most individuals living in an area with frequent prescribed burns or wildfires, meaning the levels described in many of these papers would generally parallel typical downwind exposures to BC.

### **Health Effects of BC**

There have also been several different studies that tried to determine the relationship between BC levels and the prevalence of health outcomes, such as the aforementioned study by Crabbe (2012) which found that respiratory hospital admissions were associated with black carbon concentrations recorded the previous day in the town of Darwin, Australia (RR = 1.0004 for each 1 ng/m<sup>3</sup> increase in BC, 95% CI 1.000–1.0008,  $p < 0.05$ ), which did not change strength when adjusted for flu.

Work by Balakrishnan et al. (2023) looked at pregnant women in developing nations and their exposure to household air pollutants like PM<sub>2.5</sub>, CO, and BC and the relationships between levels of these pollutants and subsequent health outcomes like birthweight. The study included 3200 women, and after accounting for miscarriages, withdrawals, and stillbirths, the authors noted that 3195 pregnancies led to 3060 live births. The mean birth weight for live births was 2909 grams, with the mean birth weight in the intervention group being 2921 grams and 2898 grams in the control group. The mean weighted exposure for BC during pregnancy was found to

be  $10.0 \mu\text{g}/\text{m}^3$ . The authors ultimately found that a  $7.3 \mu\text{g}/\text{m}^3$  reduction in prenatal BC exposure was associated with an increase in birth weight of around 22 grams.

Song et al. (2022) did a meta-analysis in order to explore the effects of BC and EC (Elemental Carbon) on cardiovascular and respiratory morbidity and mortality. Seventy studies ultimately met their criteria, which were Time series, case cross-over and cohort studies that evaluated the associations between BC/EC on cardiovascular or respiratory morbidity or mortality. They found that short-term exposure to BC/EC was associated with a 1.6% (95% CI, 0.4%-2.8%) increase in cardiovascular diseases per  $1 \mu\text{g}/\text{m}^3$  in the elderly, and that long-term exposure was associated with a 6.8% (95% CI, 0.4%-13.5%) increase in cardiovascular diseases. The authors thus concluded that both short and long-term exposures to BC/EC were related with cardiovascular diseases, although the evidence for an impact of BC/EC on respiratory diseases did not present consistent evidence and was consistent with randomness, meaning future studies are needed.

Another study by Wang et al. (2021) attempted to estimate premature mortality attributed to BC in China using a health impact model combined with predicted annual average BC concentrations. They estimated source contributions to BC from six different source sectors, including residential, transportation, industrial, open burning, power, and other sources, and then they estimated the sensitivity of BC-related premature mortality was calculated for different regions in China, with the authors finding that the total all-cause premature mortality related to BC was approximately 1,436,957 (95% CI, 998,746–2,029,210) in the whole of China in 2013. The authors note that despite the uncertainties in their estimates, controlling BC emissions in

China would lead to significant health benefits, and that controlling BC from both industrial and transportation sources would bring relative mortality reductions in most provinces of China.

There have also been several animal studies done on adverse health outcomes related to BC exposure. For example, Jiang et al. (2023) looked at the effects of oxidized BC (OBC) particles on the reproductive system of male mice. The authors note that OBC consists of spherical particles with a primary particle diameter of approximately 80 nm and a specific surface area of 38.7 m<sup>2</sup>/g. To examine effects on the male reproductive system, the authors took 30 ICR pregnant mice and assigned them to an OBC treatment group (n=15) and an untreated control group (n=15). The pregnant mice were instilled tracheally a total of 7 times during the gestation period, totalling 14µg/mouse or 466.7 µg/kg body weight. After the neonates were born, they measured seminiferous tubule damage in the mice at Postnatal day 35 and 84 and found that there was significantly more damage in the seminiferous tubules in the OBC treatment group at both day 35 and 84. Furthermore, they also observed sperm production in the newborn male mice at both day 35 and day 84, and found that there was an approximate 26.6% decrease (day 35) and an approximate 33.1% decrease (day 84) in daily sperm production in the treatment group compared to the control group. Finally, they measured serum testosterone at days 35 and 84 among the treatment and control groups, and found that at day 35 the serum testosterone in the treatment group decreased by 41.5%, and decreased by 34.8% at day 84.

Another relevant mouse study was done by Chu et al. (2018), which looked at key cytokines that participate in lung damage in mice induced by BC particles. C57BL/6 female mice were used. Seven mice were in the treatment group for BC, and were given a 200 µg dose of 30nm BC intratracheally twice for 4 weeks. Mice treated with BC showed much higher mRNA

expression of cytokines like IL-6 and IL-33 in lung tissue compared to the control group. This was also found for mRNA expression in lung tissue for chemokines like CXCL1, CXCL2, CXCL5, and CXCL10.

In vitro studies on BC have also been done, such as recent work by Shang et al. (2022), which looked at the effects of ultrafine BC (BC with aerodynamic diameter less than 100 nm) on SH-SY5Y cells, a human neuroblastoma cell line. These cells were exposed to uBC at doses of 0, 5, 10, 20, and 40  $\mu\text{g}/\text{mL}$ . The authors found that uBC caused mitochondria-mediated intrinsic apoptosis, with significant increases in apoptotic proteins like Caspase-3 and Caspase-7 at 10, 20, and 40  $\mu\text{g}/\text{mL}$ . They also found that uBC induced mitochondrial dysfunction in these cells, with relative ATP level decreasing significantly at 5, 10, 20, and 40  $\mu\text{g}/\text{mL}$  compared to the control.

Another in vitro study was done by Ge et al. (2021), which looked at BC effects on human bronchial epithelial cells from the 16HBE cell line. These cells were treated with different levels of BC over varying time spans. A cell viability assay looked at cells treated with different concentrations of BC over 24 hours. Cell viability for these cells drops precipitously starting at BC concentrations of 500  $\mu\text{g}/\text{mL}$  and 1000  $\mu\text{g}/\text{mL}$ , both of which had viability percentages below 50%.

### **Conclusions**

Based on the review of the literature, it is clear that BC is a significant pollutant from woodsmoke both in ambient and personal studies. It is also clear that BC is associated with a wide array of different health effects, affecting a variety of different processes and organ systems in the human body, even with incremental increases in BC such as 1  $\mu\text{g}/\text{m}^3$  (Song et al. 2022) or

even 1 ng/m<sup>3</sup> (Crabbe 2012). This makes the levels seen in the aforementioned literature, both in the ambient and personal studies, relevant in a public health risk context. Ambient exposure is the most common exposure route for most individuals, so this would be the most pertinent route for assessing risk for the general public. Although there have been studies on ambient levels, the literature could be helped by additional studies which could help to gain a fuller picture of potential human health risks, as BC levels can vary widely depending on the characteristics of a burn. This is what this thesis will attempt to do.

### **Scope of Thesis**

The OT21 SootScan Transmissometer allows us to scan archived samples such as those from previous studies. Teflon filters from previous studies on prescribed burns were used to determine their BC concentrations as well as their relationship to PM<sub>2.5</sub> levels. One study on ambient levels of PM<sub>2.5</sub> was located in the Savannah River Site, South Carolina in 2003, 2004, 2005, and 2007 (Pearce et al. 2012). It involved multiple air monitoring campaigns performed during prescribed burn events under select meteorological conditions (Pearce et al. 2012). The other study on ambient levels of PM<sub>2.5</sub> was conducted at Francis Marion National Forest in 2003 (Naeher et al. 2006). This study looked at prescribed burns in two plots of land at Francis Marion National Forest, one subject to mechanical chipping while the other was not.

The BC concentration will be used in several ways in this thesis. For both studies, total BC and geometric means of will be calculated. PM<sub>2.5</sub> values will be taken from an inventory of values that our lab has. The ratio of BC to PM<sub>2.5</sub> will also be calculated, as BC is a component of PM<sub>2.5</sub>. The medians and ranges of these values will also be determined. For the SRS study, an analysis of the relationship between both distance from the burn line and wind hits (percent of time a filter was downwind of a burn) with BC, PM<sub>2.5</sub>, and BC/PM<sub>2.5</sub> ratio will also be

performed. For the Francis Marion study, a two-sample t-test will also be performed to determine whether the difference in BC levels between the plots is significant.

The aforementioned literature shows some of the general levels found of BC and PM2.5 found from woodsmoke fires. This thesis will help to add to the literature on BC exposure levels from woodsmoke, particularly prescribed burns, and to the understanding of the spatiotemporal dynamics of BC levels.

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**CHAPTER 2**

**DOWNWIND EXPOSURE TO BLACK CARBON MEASURED ON PM<sub>2.5</sub> FILTERS**

**FROM PRESCRIBED BURNS AT SAVANNAH RIVER SITE<sup>1</sup>**

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<sup>1</sup>Michael R. O'Brien ; Luke P. Naeher. To be submitted to Journal of Exposure Science and Environmental Epidemiology

## **Downwind Exposure to Black Carbon Measured on PM2.5 Filters from Prescribed Burns at Savannah River Site**

### **Abstract**

**Introduction:** Woodsmoke produces various airborne pollutants, such as PM2.5 and one of its components, Black Carbon (BC).

**Objective:** To determine BC and BC/PM2.5 levels in Ambient prescribed burn samples from 2003, 2004, 2005, and 2007, as well as their relationship to burn line distance and wind hits.

**Methods:** Archived filters from four years of prescribed burns at the Savannah River Site in South Carolina were analyzed for BC using the SootScan instrument.

**Results:** Across all years (2003,2004,2005,2007) and filters (N=481), we found that for PM2.5, the Geometric mean was 32.96  $\mu\text{g}/\text{m}^3$ , the median was 27.93  $\mu\text{g}/\text{m}^3$ , the range was 7.52-1198.78  $\mu\text{g}/\text{m}^3$ , and the standard deviation was 139.69. For BC, we found that the Geometric mean across all years was 1.50  $\mu\text{g}/\text{m}^3$ , the median was 1.30  $\mu\text{g}/\text{m}^3$ , the range was 0.406-33.446  $\mu\text{g}/\text{m}^3$ , and the standard deviation was 4.19. For the BC/PM2.5 ratio, we found that the Geometric mean across all years was 0.045, the median was 0.051, the range was from 0.002-0.26, and the standard deviation was 0.028. We also used three mixed effects models to determine if there was a significant relationship between BC, PM2.5, and the BC/PM2.5 ratio with burn line distance and wind hits. We determined that for both BC and PM2.5, this relationship was significant ( $p<0.0001$ ) for both burn line distance and wind hits, with both decreasing with increasing burn line distance and increasing with increasing wind hits For BC/PM 2.5 Ratio, this relationship

was not significant for either variable.

Discussion and Conclusion: This data adds to the literature on BC levels as well as using archived filters to determine them, as well as the variables that affect BC levels during prescribed burns. The levels observed generally parallel that which is found in the literature, and these observations and dynamics could be used for risk communication to the public during prescribed burns.

### **Introduction**

Black Carbon (BC) is a component of the pollutant PM<sub>2.5</sub> that is formed through incomplete combustion of fossil fuels as well as during the burning of wood in wildfires (Coppola et al. 2022). It has been linked to various detrimental health effects such as premature mortality (Wang et al. 2021) and cardiovascular disease (Song et al. 2022), and has been implicated in Climate Change (Harmsen et al. 2020). It is an occupational exposure among wildland firefighters during prescribed burns, as has been demonstrated in past studies (Wu et al. 2021, Adetona et al. 2022).

Using the OT21 SootScan Transmissometer allows for BC analysis of archived samples. Teflon filters from four previous years of prescribed burns at the Savannah River Site (SRS) were used for analyzing their BC concentrations in relation to PM<sub>2.5</sub> concentrations. These four burn years all took place at this site in South Carolina in 2003, 2004, 2005, and 2007, with many individual burns occurring within each year. Gravimetric analysis was used to calculate PM<sub>2.5</sub> in these samples, which was reported in  $\mu\text{g}/\text{m}^3$ .

Although all of the years observed took place at the same site at SRS, they are not directly comparable due to differences in burns across each year. Both the fuel type,

meteorological conditions as well as other factors led to differences. The impact of these contributed to differences in PM<sub>2.5</sub> and/or BC levels and distributions. The BC concentration will be used in several ways in this study. Total BC concentrations will be calculated for each year. The ratio of BC to PM<sub>2.5</sub> will also be calculated, as BC is a component of PM<sub>2.5</sub>. This study will help to add to the literature on BC levels in woodsmoke and the use of SootScan technology to scan archived filters.

The study that includes the 2003, 2004, 2005, and 2007 samples took place at the Savannah River Site (SRS) during the months of December to April in the years 2003-2007 (Pearce et al. 2012). SRS is an 800 square kilometer National Environmental Research Park where extensive prescribed burning is performed (Pearce et al. 2012). Multiple systematic air monitoring campaigns were conducted to collect gridded observations of ground-level PM<sub>2.5</sub> over distances of up to ten kilometers during several prescribed burn events (Pearce et al. 2012). The map of the filters at the SRS site can be seen in Figure 2.3.

### **Methods**

The filters from 2003, 2004, 2005, and 2007 were collected from multiple air monitoring campaigns during prescribed burns at the SRS site, with the burns being conducted during the months of December through April for those years (Pearce et al. 2012). Time-integrated PM<sub>2.5</sub> samples were collected using 37-mm Teflon filters, Triplex Cyclones, and SKC Universal Pumps (SKC Inc. model 224-PCXR8), and Cyclones were attached to the pumps using 1.22 m of Tygon tubing and flow rates were set to 1.5 L min<sup>-1</sup> (Pearce et al. 2012). These samples were later weighed using a Cahn C-35 microbalance (Pearce et al. 2012).

## Addition of Black Carbon Data

One of the nondestructive methods that can be used to determine BC concentration on Teflon filters is by using the Magee Scientific SootScan Model OT21 Transmissometer (Magee Scientific Corporation, Berkeley, CA), as seen in Figure 2.1. The SootScan is the main instrument that was used in the analysis of our 37mm Teflon filters for BC. Examples of used filters can be seen in Figure 2.2. Analysis for black carbon was performed in the Naeher lab during the spring of 2024 on the original Teflon filters taken from the aforementioned study. This analysis was done by using the SootScan Dual Wavelength Optical Transmissometer according to the manual provided by Magee Scientific (Magee Scientific, 2014). We also added a diffuser filter, which is recommended for use with Teflon filters (Hansen, 2015). The SootScan provides a nondestructive method of measuring black carbon by the attenuation of infrared light (880 nm) through the filter. The transmission of a sample filter is compared to the transmission of a blank filter to provide the IR attenuation or ATN IR using the below formula

$$ATN = 100 * \ln(IRB/IRS)$$

where IRS is the sample filter's transmission and IRB is the blank filter's transmission. The attenuation can then be used to calculate the concentration of black carbon using the below formula

$$BC (\mu\text{g}/\text{m}^3) = ((\text{Filter area}(\text{m}^2)/\text{Sample volume}(\text{m}^3) * ATN * 10^4) / \sigma)$$

where  $\sigma$  is also known as the attenuation cross-section. The filter area that was used for this study was  $6.8 \text{ cm}^2$ , due to a 29.5mm diameter of exposed material for the filter. The value of

sigma used for this study was  $13.7 \text{ cm}^2/\mu\text{g}$ , based on the work by Garland et al. (Garland et al., 2017), which also used Teflon filters and looked at biomass smoke like woodsmoke.

All filters were scanned twice, and the subsequent average of the two ATN IR values generated was then used to calculate the BC concentration. All ATN IR values below the LOD (Limit of Detection) were replaced with  $\text{LOD}/\sqrt{2}$ . A representative unexposed filter was used for the blank scan.

### **Statistical Analysis**

Data analysis was performed by using SAS v.9.4 (SAS Institute Inc., Cary, NC). The data from the original studies were used for the PM<sub>2.5</sub> data, and the Gravimetric PM<sub>2.5</sub> data was matched with the BC data.

Geometric means, Medians, and Ranges were calculated for BC, PM<sub>2.5</sub>, and BC/PM<sub>2.5</sub> for all years. Furthermore, we used three mixed effects models to determine the effect of distance of filter from the burn line (in kilometers) as well as wind hits (percent of the time the filter was downwind of a burn) on BC, PM<sub>2.5</sub>, and BC/PM<sub>2.5</sub>. These three models combined the data from all of the four years, as well as all of the individual burns that had been done over the course of all of the years (47 in total). The total number of filters used after combining all of the years ended up being 481. The effect of year and individual burns were taken into account as random effects in this model in order to properly determine the effect of burn line distance and wind hits, the fixed effects, on BC, PM<sub>2.5</sub>, and BC/PM<sub>2.5</sub> levels. For this analysis, the log of BC and of PM<sub>2.5</sub> were used to account for the skewed nature of the data, while BC/PM<sub>2.5</sub> was calculated using the original, untransformed, data. All of this analysis was done in SAS v9.4. Statistical significance was considered  $p < 0.05$  in this study.

## Results

### Descriptive Data across all years

Across all years (2003,2004,2005,2007) and filters (N=481), we found that for PM2.5, the Geometric mean was 32.96  $\mu\text{g}/\text{m}^3$ , the median was 27.93  $\mu\text{g}/\text{m}^3$ , the range was 7.52-1198.78  $\mu\text{g}/\text{m}^3$ , and the standard deviation was 139.69. For BC, we found that the Geometric mean across all years was 1.50  $\mu\text{g}/\text{m}^3$ , the median was 1.30  $\mu\text{g}/\text{m}^3$ , the range was 0.406-33.446  $\mu\text{g}/\text{m}^3$ , and the standard deviation was 4.19. Finally, for BC/PM2.5, we found that the Geometric mean across all years was 0.045, the median was 0.051, the range was from 0.002-0.26, and the standard deviation was 0.028.

### Mixed Effects Model Analysis

The mixed-effects model predicts that logBC decreased by 0.118 (95% CI, 0.091,0.145) for each km increase in burn line distance ( $p < 0.0001$ ,  $t$ -test). The model also predicted logBC increased by 0.011 (95% CI, 0.009, 0.014) for every percent increase in a wind hit ( $p < 0.0001$ ,  $t$ -test). According to the model, the within burn variance component (0.425) was about three times greater than the between burn variance component (0.123), indicating there was significantly more variability among logBC levels within burns than between burns. The estimated between year variance component was zero suggesting that variability between years in BC levels was negligible.

The mixed effects model predicts that logPM2.5 decreased by 0.102 (95% CI, 0.134, 0.070) for each km increase in burn line distance ( $p < 0.0001$ ,  $t$ -test). The model also found that

logPM2.5 increased by 0.011 (95% CI, 0.008, 0.014) for every percent increase in a wind hit ( $p < 0.0001$ , *t*-test). According to the model, the within burn variance component (0.5598) was almost four times greater than the between burn variance component (0.1849), indicating there was significantly more variability among logPM2.5 levels within burns than between burns. The estimated between year variance component was 0.0556 suggesting that variability between years in logPM2.5 levels was fairly low.

The mixed effects model predicts that BC/PM2.5 decreased by 0.00027 (95% CI, -0.00125, 0.00072) for every km increase in burn line ( $p = 0.5957$ , *t*-test). The model also found that the BC/PM2.5 ratio decreased by  $6.38 \times 10^{-6}$  (95% CI, -0.00011, 0.00009) for every percent increase in a wind hit ( $p = 0.9009$ , *t*-test). According to the model, the within burn variance component (0.000534) was about three times greater than the between burn variance component (0.000189), indicating there was significantly more variability among BC/PM2.5 levels within burns than between burns. The estimated between year variance component was 0.000193 suggesting that variability between years in BC/PM2.5 levels was fairly low.

The relationship between PM2.5 and Burn Line Distance is seen in Figure 2.4. Furthermore, we can conclude that BC is related to Burn Line Distance in a significant way, as can be seen in Figure 2.5. Both decrease with increasing Burn Line Distance, confirming that this is one of the variables important in affecting the levels of these pollutants. No significant relationship could be seen between BC/PM2.5 and Burn Line Distance, which can be seen visually in Figure 2.6.

The relationship between PM<sub>2.5</sub> and Wind hits across various distances is seen in Figure 2.7. We can also conclude that BC is related to Wind hits in a significant manner, but this relationship is also only relevant at close distances from the burn line, as seen in Figure 2.8. Both PM<sub>2.5</sub> and BC were seen to increase with increasing wind hits, confirming that this is an important variable for affecting the levels of both of these pollutants. No significant relationship could be found between BC/PM<sub>2.5</sub> and wind hits, which is seen visually in Figure 2.9.

### **Discussion**

The values we have found for these ambient samples are largely comparable to values gathered from previous studies on ambient levels of BC from woodsmoke. For example, Ivanic et al. (2023) analyzed the Camp Fire's influence on air quality in Northern California by measuring black carbon (BC) using the Carbonaceous Aerosol Speciation System at a site in Berkeley, California. This study reported median Black Carbon levels, which were 1  $\mu\text{g}/\text{m}^3$  before the fire and about 4  $\mu\text{g}/\text{m}^3$  for phases I and II of the fire. The median value of 1  $\mu\text{g}/\text{m}^3$  is close to the median value we found for our own study, which was 1.30  $\mu\text{g}/\text{m}^3$ .

Furthermore, Healy et al. (2019) looked at Aethalometer data collected at six sites in the Lower Fraser Valley (LFV), British Columbia, using a dual-wavelength Model AE22 Aethalometer to determine BC values. They looked at data from September 2016 to August 2017 to determine the relative importance of fossil fuel and biomass burning contributions to BC in the region. They found BC levels that ranged from about 0 to 6  $\mu\text{g}/\text{m}^3$  and PM<sub>2.5</sub> levels that ranged from about 0 to 150  $\mu\text{g}/\text{m}^3$  during that time period. This range for BC levels is similar to

the Geometric mean and medians that we found, which were  $1.50 \mu\text{g}/\text{m}^3$  and  $1.30 \mu\text{g}/\text{m}^3$ , while the upper end of our range ended up being much higher,  $33.45 \mu\text{g}/\text{m}^3$ .

Selimovic et al. (2019) looked at major wildfire smoke and haze that impacted the Northwestern US from a station in Missoula, Missouri found a PM<sub>2.5</sub> range of about 0-471  $\mu\text{g}/\text{m}^3$  and 0 to 3.62  $\mu\text{g}/\text{m}^3$  for BC. Particle absorption and scattering coefficients were measured directly at 1s time resolution using two photoacoustic extinctionimeters (PAX, Droplet Measurement Technologies, Inc., Longmont, CO), which were then used to calculate BC concentration. The range of BC values that these authors find include most of the values that we found for BC, although much higher values were also found.

While there is currently no regulatory standard determining safe or hazardous levels of Black Carbon as there is for PM 2.5, several health hazards of BC have been established in the literature. There have also been several studies determining the relationship between BC levels and the prevalence of health outcomes, such as the aforementioned study by Crabbe (2012) which determined that Respiratory hospital admissions were associated with black carbon concentrations recorded the previous day (RR = 1.0004 for each  $1 \text{ ng}/\text{m}^3$  increase in BC, 95% CI 1.000–1.0008,  $p < 0.05$ ), which did not change strength when adjusted for flu.

Balakrishnan et al. (2023) looked at pregnant women in developing nations and their exposure to household air pollutants like PM<sub>2.5</sub>, CO, and BC and the relationships between levels of these pollutants and subsequent health outcomes like birthweight. The study included 3200 women, and after accounting for miscarriages, withdrawals, and stillbirths, 3195 pregnancies led to 3060 live births. The mean birth weight for live births was 2909 grams, with the mean birth weight in the intervention group being 2921 grams and 2898 grams in the control

group. The mean weighted exposure for BC during pregnancy was found to be  $10.0 \mu\text{g}/\text{m}^3$ . The authors found that a  $7.3 \mu\text{g}/\text{m}^3$  reduction in prenatal BC exposure was associated with an increase in birth weight of around 22 grams.

Wang et al. (2021) attempted to estimate premature mortality attributed to BC in China using a health impact model combined with predicted annual average BC concentrations. They estimated source contributions to BC from six different source sectors, including residential, transportation, industrial, open burning, power, and other sources. Then the sensitivity of BC-related premature mortality was calculated for different regions in China, with the authors finding that the total all-cause premature mortality related to BC was approximately 1,436,957 (95% CI, 998,746–2,029,210) in China in 2013. The authors note that despite the uncertainties in their estimates, controlling BC emissions in China would lead to significant health benefits, and that controlling BC from both industrial and transportation sources would bring relative mortality reductions in most provinces of China.

Song et al. (2022) did a meta-analysis in order to explore the effects of BC and EC (Elemental Carbon) on cardiovascular and respiratory morbidity and mortality. They found that short-term exposure to BC/EC was associated with a 1.6% (95% CI, 0.4%-2.8%) increase in cardiovascular diseases per  $1 \mu\text{g}/\text{m}^3$  in the elderly, and that long-term exposure was associated with a 6.8% (95% CI, 0.4%-13.5%) increase in cardiovascular diseases. The authors thus concluded that both short and long-term exposures to BC/EC were related with cardiovascular diseases, although the evidence for an impact of BC/EC on respiratory diseases did not present consistent evidence and further investigations are needed.

There have also been several animal studies done on adverse health outcomes related to BC exposure. Jiang et al. (2023) looked at the effects of oxidized BC (OBC) particles on the reproductive system of male mice. The authors note that OBC consists of spherical particles with a primary particle diameter of approximately 80 nm and a specific surface area of 38.7 m<sup>2</sup>/g. To examine effects on the male reproductive system, the authors took 30 ICR pregnant mice and assigned them to an OBC treatment group (n=15) and an untreated control group (n=15). The pregnant mice were instilled via the trachea 7 times during the gestation period, totalling 14µg/mouse or 466.7 µg/kg body weight. After the neonates were born, they measured seminiferous tubule damage in the mice at Postnatal day 35 and 84 and found that there was significantly more damage in the seminiferous tubules in the OBC treatment group at both day 35 and 84. Furthermore, they also observed sperm production in the newborn male mice at both day 35 and day 84, and found that there was an approximate 26.6% decrease (day 35) and an approximate 33.1% decrease (day 84) in daily sperm production in the treatment group compared to the control group. Finally, they measured serum testosterone at days 35 and 84 among the treatment and control groups, and found that at day 35 the serum testosterone in the treatment group decreased by 41.5%, and decreased by 34.8% at day 84.

Another relevant mouse study was done by Chu et al. (2018), which looked at key cytokines that participate in lung damage in mice induced by BC particles. C57BL/6 female mice were used. Seven mice were in the treatment group for BC, and were given a 200 µg dose of 30nm BC intratracheally twice for 4 weeks. Mice treated with BC showed much higher mRNA expression of cytokines like IL-6 and IL-33 in lung tissue compared to the control group. This was also found for mRNA expression in lung tissue for chemokines like CXCL1 and CXCL2.

A few in vitro studies on the effects of BC have also been done, such as work done by Ge et al. (2021), which looked at BC effects on human bronchial epithelial cells. These cells were treated with different levels of BC over varying time spans. A cell viability assay looked at cells treated with different concentrations of BC over 24 hours. Cell viability for these cells dropped precipitously starting at BC concentrations of 500  $\mu\text{g}/\text{mL}$  and 1000  $\mu\text{g}/\text{mL}$ , both of which had viability percentages below 50%.

Another in vitro study for BC was done by Shang et al. (2022), which looked at the effects of ultrafine BC (BC with aerodynamic diameter less than 100 nm) on SH-SY5Y cells, a human neuroblastoma cell line. These cells were exposed to uBC at doses of 0, 5, 10, 20, and 40  $\mu\text{g}/\text{mL}$ . The authors found that uBC caused apoptosis, with significant increases in proteins involved in apoptosis like Caspase-3 and Caspase-7 at 10, 20, and 40  $\mu\text{g}/\text{mL}$ . They also found that uBC induced mitochondrial dysfunction in these cells, with relative ATP level decreasing significantly at 5, 10, 20, and 40  $\mu\text{g}/\text{mL}$  compared to the control.

With regards to our model results, The mixed effects models used showed that there is a significant relationship between PM2.5 as well as BC and distance from the burn line, after taking into account the random effects of the year as well as the individual burn. These relationships can be seen in Figures 2.4 and 2.5. This was not the case for BC/PM2.5, which is seen in Figure 2.6. The mixed mixed effects models also showed that there is a significant relationship between PM2.5 as well as BC and wind hits, after taking into account the random effects of the year as well as the individual burn. These relationships can be seen in Figures 2.7 and 2.8, which show that this relationship only seems to be relevant at close distances from the burn line. There was no significant relationship between BC/PM2.5 and wind hits,

which can be seen in Figure 2.9.

In conclusion, with regards to levels of BC, while we cannot technically state the exact nature of the levels we found as safe or unsafe, as no current standard exists, it is clear from the existing literature that BC is associated with several adverse health outcomes. These include outcomes such as birth weight, respiratory hospital admissions, and cardiovascular disease. These outcomes appear to be dose-dependent, increasing risk for cardiovascular disease for every 1  $\mu\text{g}/\text{m}^3$  increase in short term exposure to BC in the elderly, as noted in the meta-analysis by Song et al. (2022) or even increasing respiratory hospital admissions appreciably for every 1  $\text{ng}/\text{m}^3$  increase (Crabbe 2012), making the levels we find in our study relevant in a risk context. This indicates that prescribed burns, depending on their nature, can lead to levels of BC that can cause marked increases in several adverse health outcomes, making BC from these burns a valid public health concern.

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### **Data Availability Statement**

Data is available from authors upon request.

### **Competing Interests**

The authors declare no competing interests.

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## **CHAPTER 3**

# **DOWNWIND EXPOSURE TO BLACK CARBON MEASURED ON PM<sub>2.5</sub> FILTERS FROM PRESCRIBED BURN AT FRANCIS MARION NATIONAL FOREST<sup>1</sup>**

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<sup>1</sup>Michael R. O'Brien ; Luke P. Naeher. To be submitted to Journal of Exposure Science and Environmental Epidemiology

## **Downwind Exposure to Black Carbon Measured on PM 2.5 Filters from Prescribed Burn at Francis Marion National Forest**

### **Abstract**

**Introduction:** An important pollutant that is produced by woodsmoke is Black Carbon (BC), a component of PM<sub>2.5</sub>.

**Objective:** To determine BC and BC/PM<sub>2.5</sub> levels in filters from two plots of a prescribed burn at Francis Marion National Forest, one subject to mechanical chipping and one that was not. Based on prior literature, the differences between these plots could lead to differences in burn characteristics.

**Methods:** The Teflon filters used in this study were stored in -20°C freezers in the Naehar lab until they were taken out and scanned for BC levels using the SootScan instrument.

**Results:** For the Chipped plot filters (N=13), we found that the Geometric Mean for BC was 6.30 µg/m<sup>3</sup>. For the BC/PM<sub>2.5</sub> ratio, the Geometric Mean was found to be 0.031. For the Unchipped plot filters (N=13), we found that the Geometric Mean for BC was 8.69 µg/m<sup>3</sup>. For the BC/PM<sub>2.5</sub> ratio, the Geometric Mean was found to be 0.018. A Two-sample *t*-test was performed that found that the differences in means between the Chipped and Unchipped plots was not significant (p=0.6910).

**Discussion:** Although no significant difference was found, the data adds to the literature on BC from prescribed burns, and is the first study to our knowledge that looks at BC differences based on differences in chipping status for different plots.

## Introduction

In recent years, the prevalence of forest fires have been increasing, particularly in the Western United States, due in part to anthropogenic climate change (Juang et al. 2022). Increased fires in the United States leads to the potential problem of downwind exposures of different pollutants like Black Carbon (BC) among the general public. Risk communication of the risk of exposure to BC as well as other pollutants would be important in interactions with the public during fires in the future.

Black Carbon (BC) is a component of the pollutant PM<sub>2.5</sub> that is formed through incomplete combustion, which may occur with the burning of fossil fuels and with the burning of wood (Coppola et al. 2022). It has been linked to various detrimental health effects such as respiratory hospital admissions (Crabbe 2012) and decreased birth weight (Balakrishnan et al. 2023).

In this study, we looked at archived Teflon filters in order to calculate BC concentrations. The ratio of BC to PM<sub>2.5</sub> will also be calculated, as BC is a component of PM<sub>2.5</sub>. This study will help to contribute to the literature on BC levels from woodsmoke and prescribed burns. The Francis Marion filters were collected from two plots located on the Francis Marion National Forest in South Carolina during prescribed burns on February 12 2003 (Naehler et al. 2006). One of the plots had been subject to mechanical chipping, while the other had not, and the primary objective of the study where it was originally reported was to measure PM<sub>2.5</sub> and Carbon Monoxide (CO) exposures from prescribed burn smoke from a mechanically chipped vs. non-chipped site (Naehler et al. 2006). The map of the plots at Francis Marion National Forest can be seen at Figure 3.1.

## Methods

The PM<sub>2.5</sub> samples from this study were collected by SKC pumps drawing air at a rate of 4.01/min through a BGI KTL cyclone and by SKC Air Check 2000 pumps drawing air at a rate of 1.51/min through a BGI Triplex Cyclone (Naehrer et al. 2006). Both Cyclone types used 37-mm Teflon filters for the particles to adhere to, and these samples later underwent gravimetric analysis using a Cahn C-35 microbalance (Naehrer et al. 2006).

### Addition of Black Carbon Data

Analysis for BC was performed in the Naehrer lab during the spring of 2024 on the original Teflon filters taken from the study. This analysis was done by using the SootScan Dual Wavelength Optical Transmissometer according to the manual provided by Magee Scientific (Magee Scientific, Berkeley, California, 2014). A diffuser filter was also used, which is recommended with Teflon filters because of the excess light that can pass through (Hansen, 2015). The SootScan provides a simple and nondestructive method of measuring BC by the attenuation of infrared or IR light (880 nm). The transmission of a sample filter is compared to the transmission of a blank filter to provide the IR attenuation or ATN IR using the below formula

$$ATN = 100 * \ln(IRS/IRB)$$

where IRS is the sample filter's transmission and IRB is the blank filter's transmission. These attenuation values can then be used to approximately calculate the concentration of BC using the below formula

$$BC (\mu\text{g}/\text{m}^3) = ((\text{Filter area}(\text{m}^2)/\text{Sample volume}(\text{m}^3) * ATN * 10^4) / \sigma$$

where  $\sigma$  is also known as the attenuation cross-section. The filter area that was used for this study was  $6.8 \text{ cm}^2$ , due to a 29.5mm diameter of exposed material for the filter (taking into account an unexposed plastic ring around the filter). The value of sigma used for this study was  $13.7 \text{ cm}^2/\mu\text{g}$ , based on the work by Garland et al. (Garland et al., 2017), which also used Teflon filters and looked at biomass smoke like woodsmoke.

All filters were scanned twice, and the subsequent average of the two ATN IR values generated was then used to calculate the BC concentration. A representative unexposed filter was used for the blank scan.

### **Statistical Analysis**

Data analysis was performed by using SAS v.9.4 (SAS Institute Inc., Cary, NC). The data from the original studies were used for the PM<sub>2.5</sub> data, and the Gravimetric PM<sub>2.5</sub> data was matched with the BC data.

Geometric means, Medians, and Ranges were calculated for BC and BC/PM<sub>2.5</sub> for both plots. A two-sample *t*-test was also done to compare the BC means for significance. Statistical significance was considered  $p < 0.05$  in this study.

### **Results**

The results for the Chipped and Unchipped plots are listed below, and they can also be found at Table 3.1. For the Chipped plot filters (N=13), we found that the Geometric Mean for BC was  $6.30 \mu\text{g}/\text{m}^3$ . The median was  $4.87 \mu\text{g}/\text{m}^3$  and the range was from 1.42 to  $30.97 \mu\text{g}/\text{m}^3$ .

For PM<sub>2.5</sub>, the Geometric Mean was 205.02  $\mu\text{g}/\text{m}^3$ , the median was 239.72  $\mu\text{g}/\text{m}^3$ , and the range was from 22 to 609.68  $\mu\text{g}/\text{m}^3$ . For the BC/PM<sub>2.5</sub> ratio, the Geometric Mean was found to be 0.031, while the median was 0.026 and the range was from 0.015 to 0.064.

For the Unchipped plot filters (N=13), we found that the Geometric Mean for BC was 8.69  $\mu\text{g}/\text{m}^3$ . The median was 10.41  $\mu\text{g}/\text{m}^3$  and the range was from 2.29 to 19.58  $\mu\text{g}/\text{m}^3$ . For PM<sub>2.5</sub>, the Geometric Mean was 475.50  $\mu\text{g}/\text{m}^3$ , the median was 596.7  $\mu\text{g}/\text{m}^3$ , and the range was from 13.6 to 1119.48  $\mu\text{g}/\text{m}^3$ . For the BC/PM<sub>2.5</sub> ratio, the Geometric Mean was found to be 0.018, while the median was 0.018. The range was from 0.0072 to 0.17. The relationship between Chipped and Unchipped Geometric Means for BC and BC/PM<sub>2.5</sub> can be seen in Figures 3.2 and 3.3, respectively.

A Two-sample *t*-test was performed in SAS, which found that the differences in means between the Chipped and Unchipped plots was not significant ( $p=0.6910$ ).

## **Discussion**

The levels of BC we found in both the Chipped and Unchipped plots were much higher than what is generally found in the literature. For example, Ivanic et al. (2023) analyzed the Camp Fire's influence on air quality in Northern California by BC levels and found that for median BC levels were 1  $\mu\text{g}/\text{m}^3$  before the fire and about 4  $\mu\text{g}/\text{m}^3$  for phases I and II of the fire. Both of these values are lower than the median value for the Chipped plot filters of 4.87  $\mu\text{g}/\text{m}^3$  and much lower than the median value for the Unchipped plot median of 10.41  $\mu\text{g}/\text{m}^3$ .

Another example would be that Selimovic et al. (2019) looked at major wildfire smoke and haze that impacted the Northwestern US from a station in Missoula, Missouri and found

values from 0 to 3.62  $\mu\text{g}/\text{m}^3$  for BC, which was much narrower than the range for both the Chipped plot (1.42 to 30.97  $\mu\text{g}/\text{m}^3$ ) and the Unchipped plot (2.29 to 19.58  $\mu\text{g}/\text{m}^3$ ). This was also the case for what Kang et al. (2014) found, which examined BC levels from two fires in Quebec, Canada in 2002 and 2010. The authors found that BC levels ranged from about 0.5 to 3  $\mu\text{g}/\text{m}^3$ , while in the 2010 fire it ranged from about 0.5 to 6  $\mu\text{g}/\text{m}^3$ . One explanation for this difference is that the Francis Marion sample filters were in much closer proximity to the actual fires than those in these other papers.

As mentioned, BC has been linked to various detrimental health effects such as respiratory hospital admissions (Crabbe 2012) and decreased birth weight (Balakrishnan et al. 2023). Mice studies have also shown that BC exposure can cause damage to the male reproductive system (Jiang et al. 2023) and increases inflammatory cytokines and chemokine expression in lung tissue (Chu et al. 2018). In vitro studies have also shown that BC can decrease cellular viability in human bronchial cells (Ge et al. 2021) and can also cause mitochondrial dysfunction (Shang 2022). One meta-analysis by Song et al. in 2022 found that there was an appreciable increase in risk for cardiovascular disease in the elderly for every 1  $\mu\text{g}/\text{m}^3$  increase in BC exposure, and the aforementioned study by Crabbe (2012) found an appreciable increase in respiratory hospital admissions for every 1  $\text{ng}/\text{m}^3$  increase, making the relatively high levels (compared to other ambient studies) found in this study very relevant in a public health context.

Overall, these results help to add to the existing literature on BC levels from prescribed burns. They also, to the best of our knowledge, are the first time anyone has compared BC levels between a plot that was subject to mechanical chipping and one that was not. As mentioned, this difference was not significant and is limited by the problem of pseudoreplication. A potential

future research direction could involve replicating this study while addressing the problem of pseudoreplication, which this study faces (Hulbert 1984). This would be done by actually replicating the chipping treatment in different plots.

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The authors would like to acknowledge Janez Krasovec and Dan Ruth from Magee Scientific for their help with the SootScan.

### **Data Availability Statement**

Data is available from authors upon request.

### **Competing Interests**

The authors declare no competing interests.

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## CHAPTER 4

### CONCLUSIONS

Levels of Black Carbon, a component of PM<sub>2.5</sub> found in woodsmoke, were determined in both the SRS and Francis Marion studies using the SootScan instrument.

For the SRS study, we determined BC and BC/PM<sub>2.5</sub> values for all four years, 2003, 2004, 2005, and 2007, constituting 481 filters in total, the results of which can be seen in Table 4.1. Furthermore, we used three mixed effects models that looked at the relationship between PM<sub>2.5</sub>, BC, and BC/PM<sub>2.5</sub> and burn line distance and wind hits. These models took into account the random effects of year as well as individual burns. We determined that for both logBC and logPM<sub>2.5</sub>, this relationship was significant ( $p < 0.0001$ ) for both burn line distance and wind hits, with both decreasing with increased burn line distance and increasing with increased wind hits. For BC/PM<sub>2.5</sub> Ratio, this relationship was not significant for either burn line distance or wind hits. According to the models, the within burn variance component was generally about three to four times greater than the between burn variance component, indicating there was significantly more variability among BC, PM<sub>2.5</sub>, and BC/PM<sub>2.5</sub> levels within burns than between burns.

For the Francis Marion study, we found that for the chipped plot filters (N=13), the Geometric Mean for BC was 6.30  $\mu\text{g}/\text{m}^3$ . For the BC/PM<sub>2.5</sub> ratio, the Geometric Mean was 0.031. For the Unchipped plot filters (N=13), we found that the Geometric Mean for BC was 8.69  $\mu\text{g}/\text{m}^3$  and the Geometric Mean of the BC/PM<sub>2.5</sub> ratio was found to be 0.018. A

Two-sample T test was performed that found that the differences in means between the Chipped and Unchipped plots was not significant ( $p=0.6910$ ).

Both the SRS study and the Francis Marion study help to add to the existing literature on BC levels from prescribed burns, and the SRS study in particular helps to assess the spatiotemporal dynamics of BC levels from prescribed burns. No comparable study on the spatiotemporal dynamics of BC levels from prescribed burns have been done to the best of our knowledge. The relationships and levels that we found here could have implications for how prescribed burns could be conducted, as well as the way risk is communicated to the general population in surrounding areas that are near the prescribed burn. This is because even small increases in BC can lead to appreciable increases in adverse health outcomes (Crabbe 2012, Song X. et al. 2022), making the levels we found in both studies relevant in a public health context. Future directions in this work could include monitoring BC levels downwind of a burn in residential or more densely populated areas.

Table 2.1. SRS Samples Results Summary Table

Pollutant	Filters	Geometric Mean	Median	Range	Standard Deviation	Standard Error
PM2.5 (µg/m <sup>3</sup> )	481	32.96	27.93	7.52-1198.78	139.69	6.37
BC (µg/m <sup>3</sup> )	481	1.50	1.30	0.41-33.45	4.19	0.19
BC/PM2.5	481	0.045	0.051	0.002-0.26	0.028	0.0013



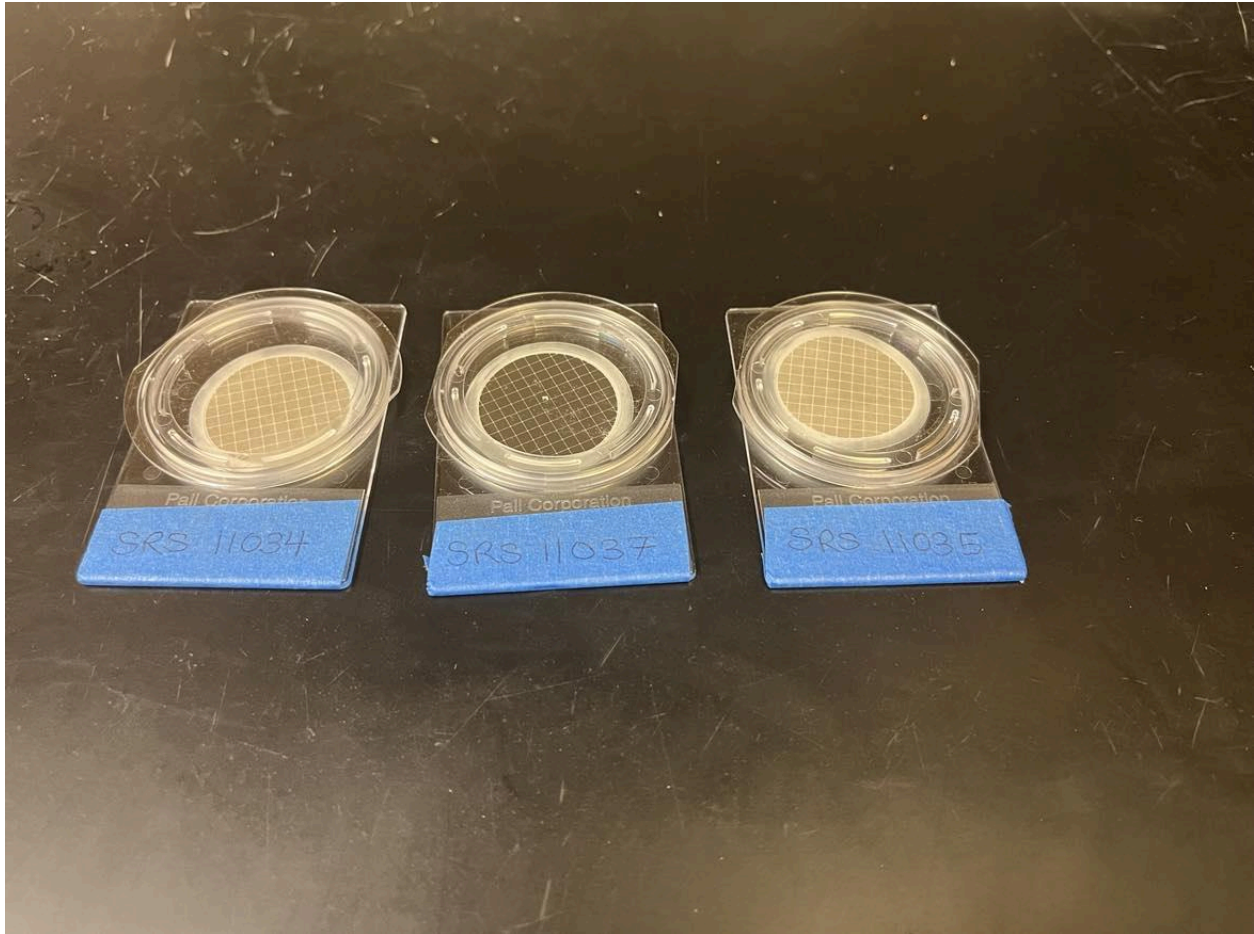


Figure 2.2 Filters exposed to BC and PM<sub>2.5</sub> emissions from wildland fires. The filters were stored in the freezers of the Naehar lab at the University of Georgia. The presence of PM<sub>2.5</sub> and BC are visible on the filters based on the coloration.

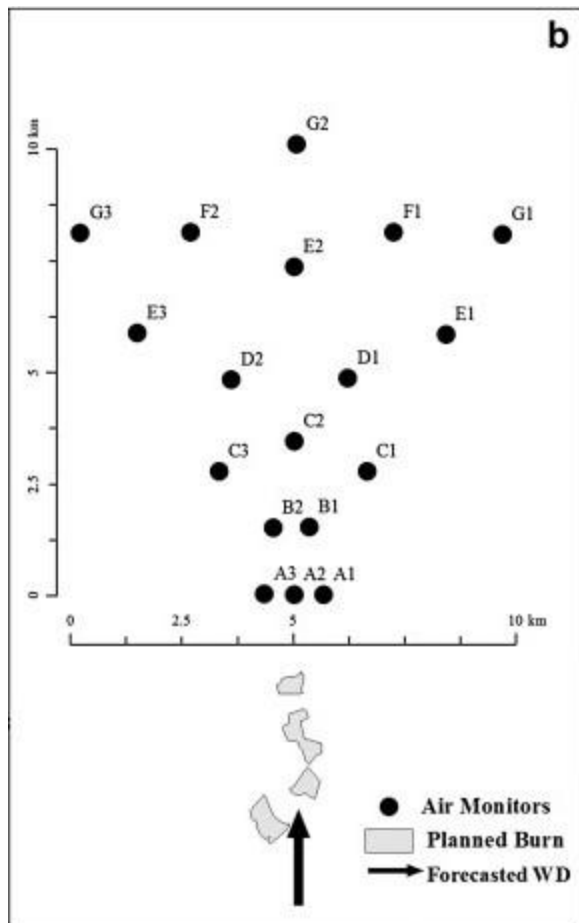


Figure 2.3. Location of air monitors in SRS study for years 2003, 2004, 2005, and 2007 relative to planned burn (Source: Pearce et al. 2012)

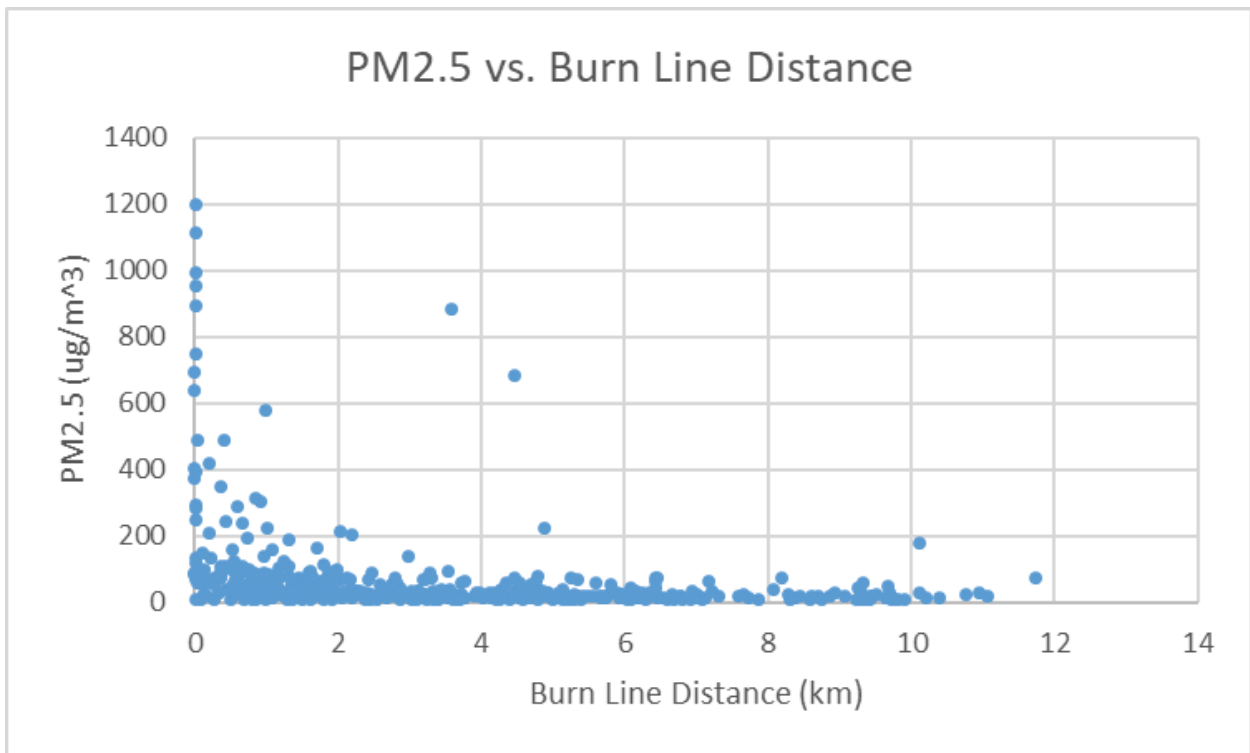


Figure 2.4. PM2.5 vs. Burn Line Distance for all filters

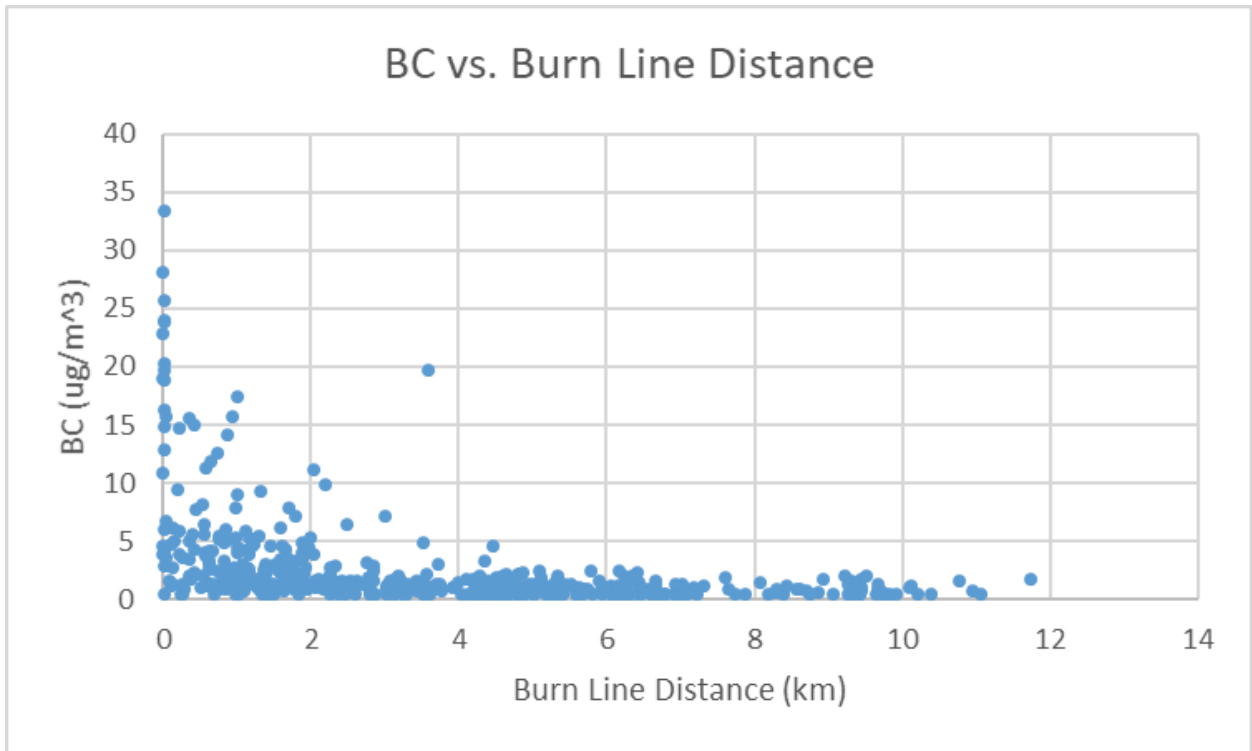


Figure 2.5 BC vs. Burn Line Distance for all filters

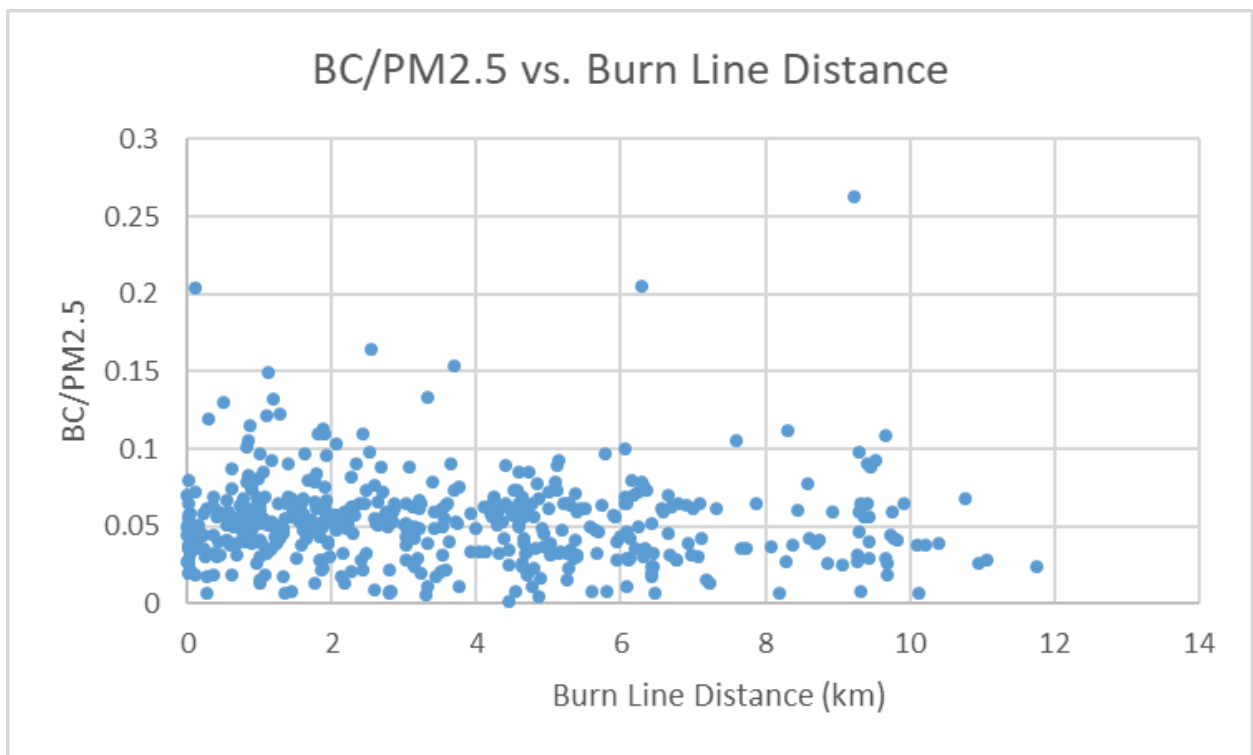


Figure 2.6. BC/PM2.5 vs. Burn Line Distance for all filters

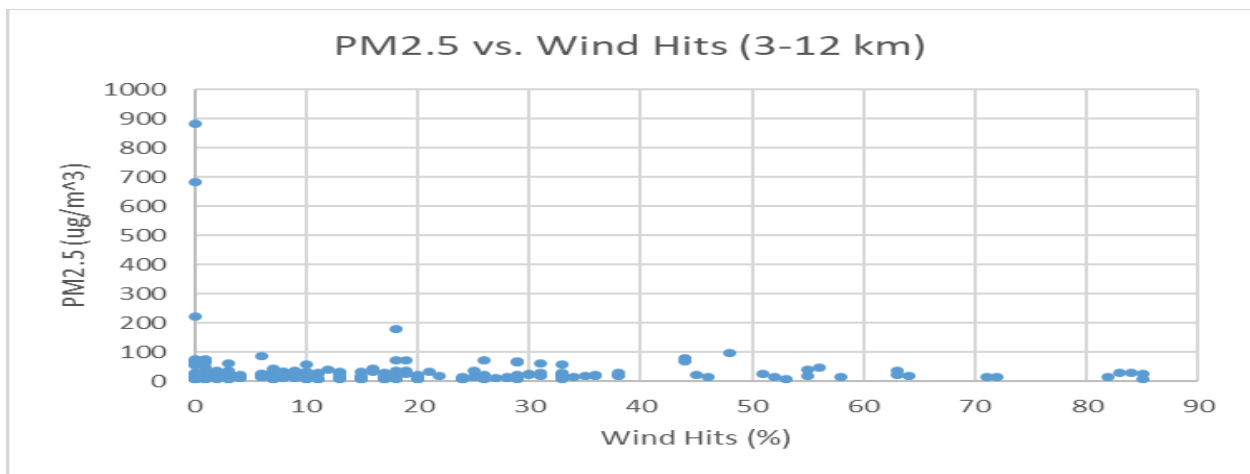
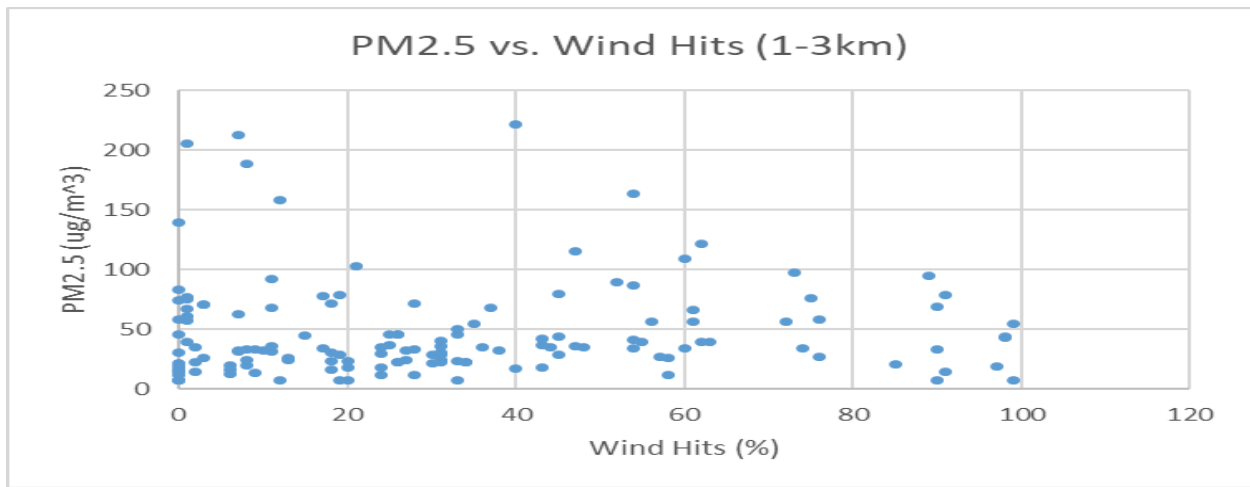
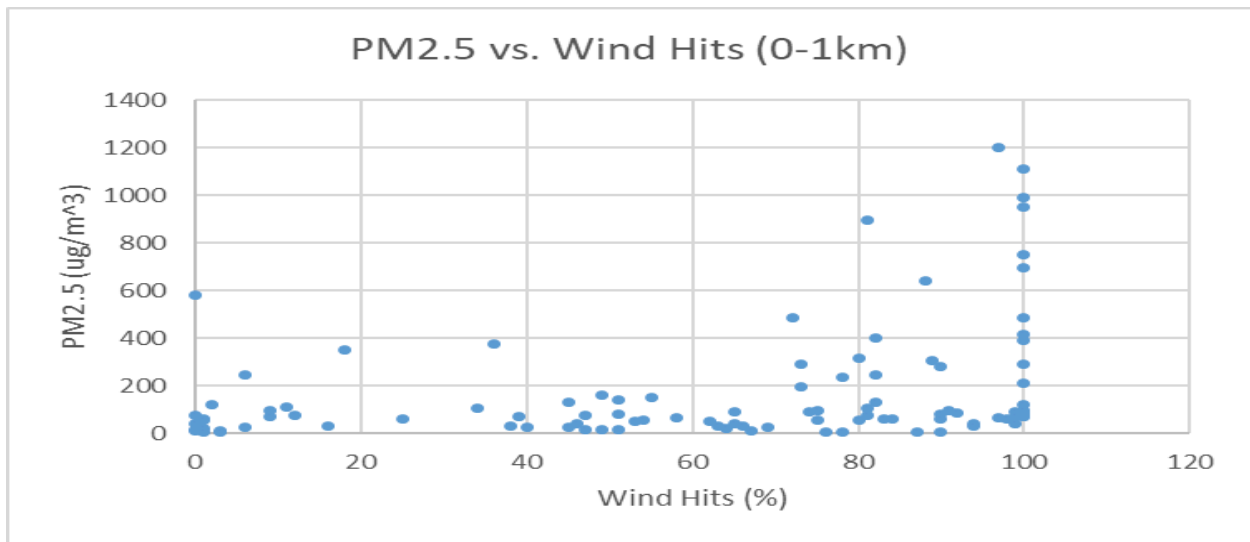


Figure 2.7. PM2.5 vs. Wind Hits across different Burn Line Distances

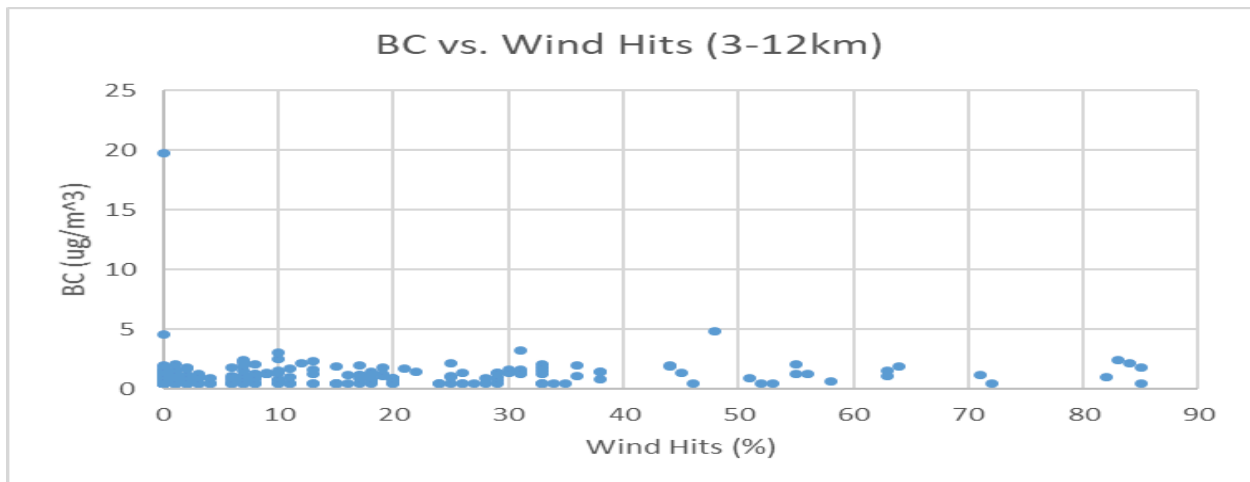
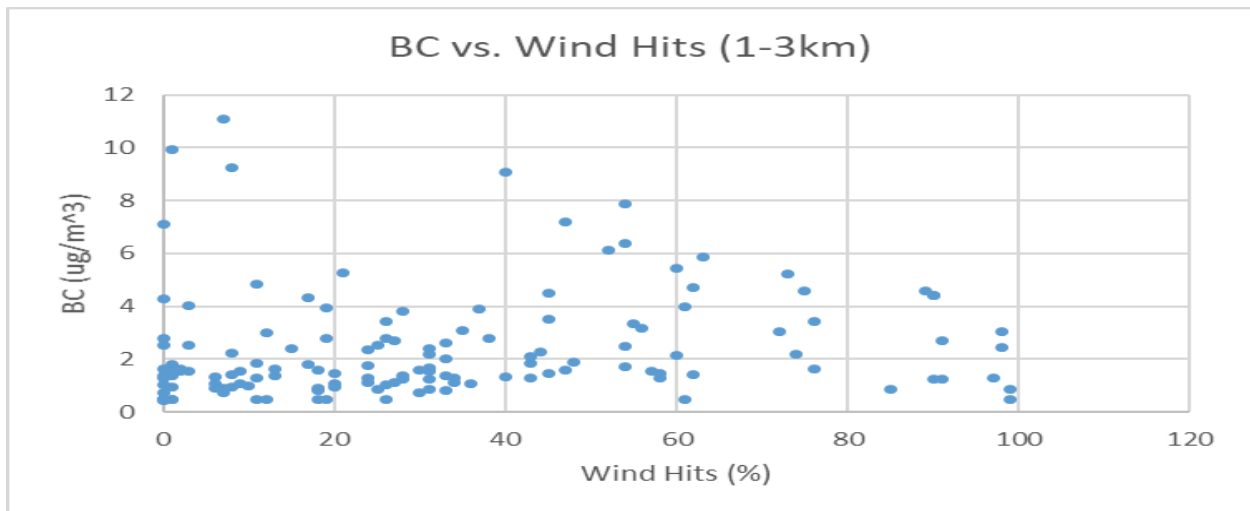
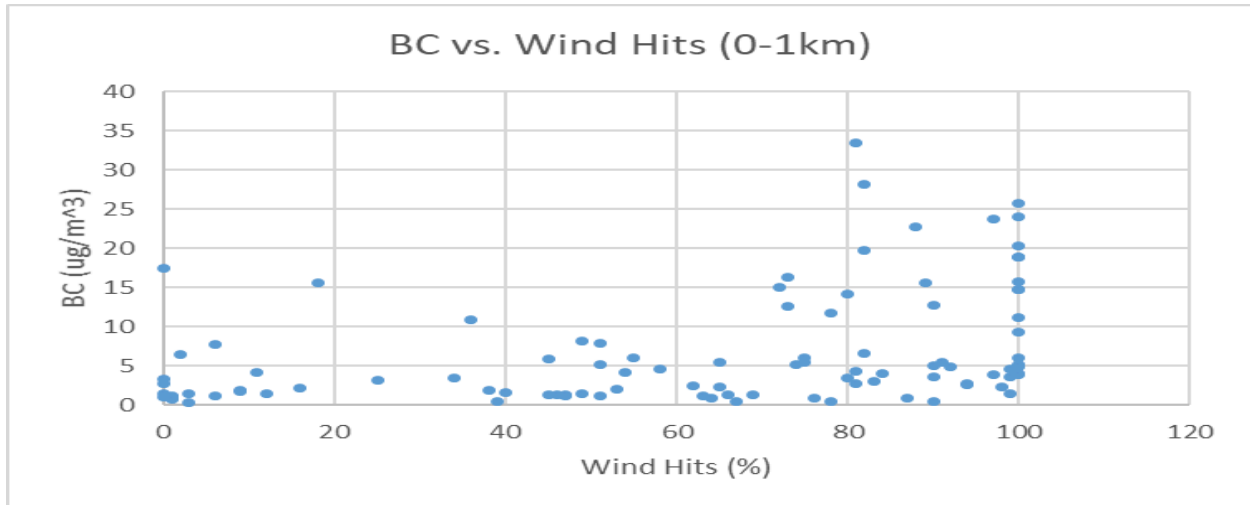


Figure 2.8. BC vs. Wind Hits across different Burn Line Distances

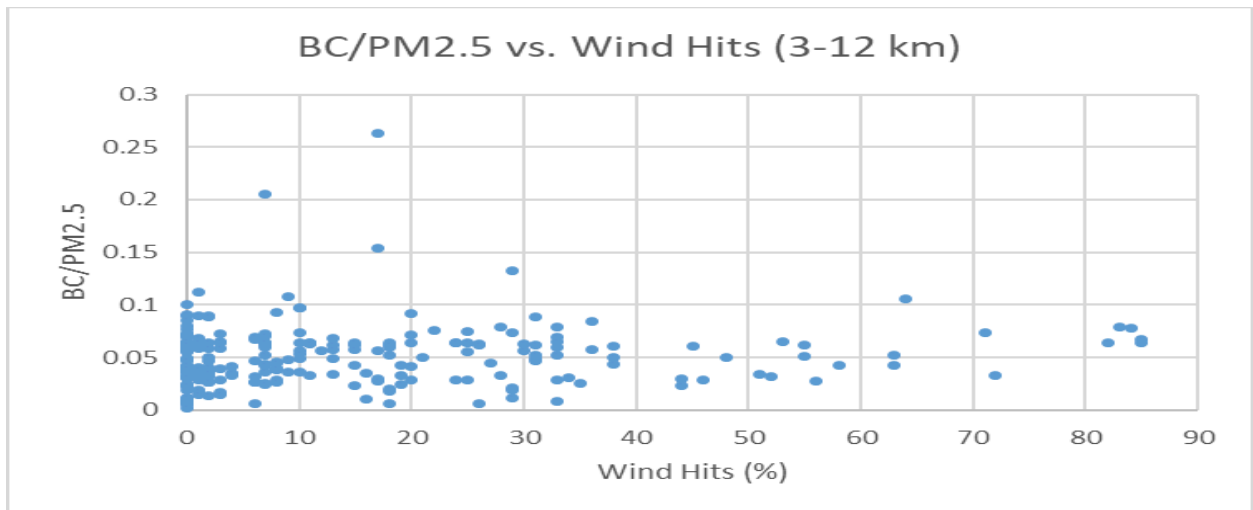
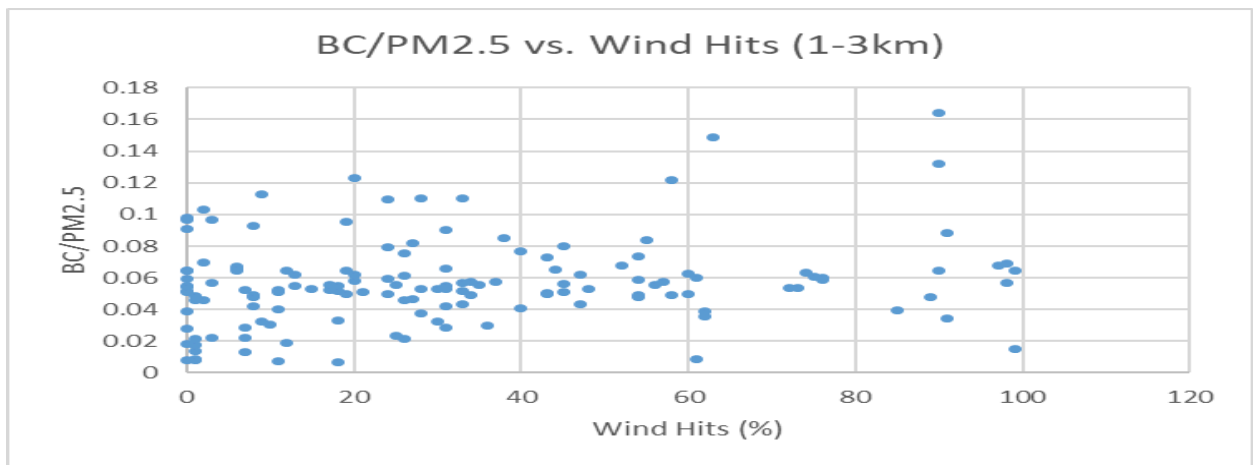
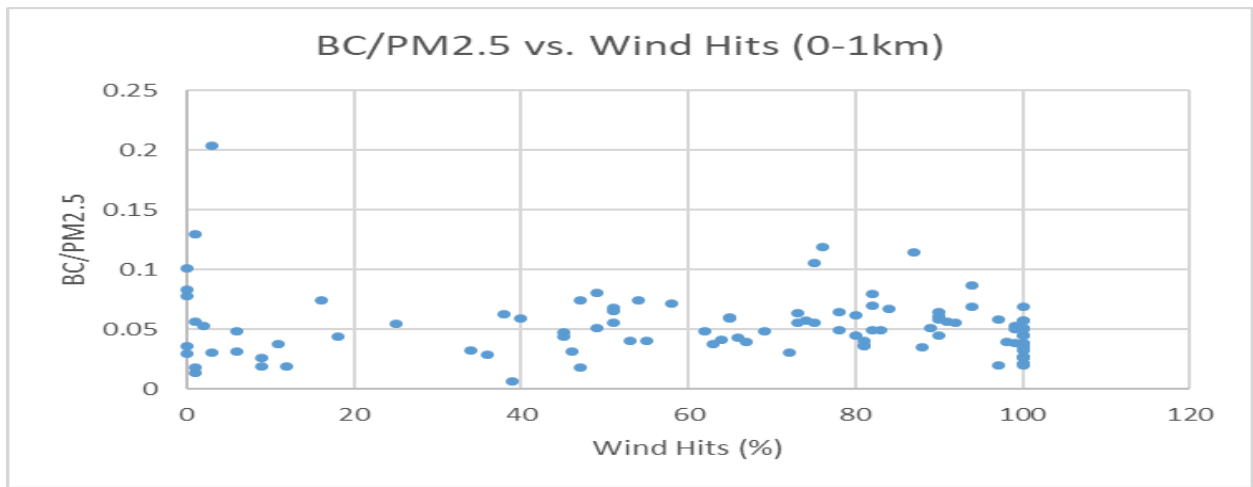


Figure 2.9 BC/PM2.5 vs. Wind hits across different Burn Line Distances

Table 3.1. FMNF Samples Results Summary Table (N=13 for both plots)

Variable	Chipping Status	Variable		
		PM2.5 µg/m <sup>3</sup>	BC µg/m <sup>3</sup>	BC/PM2.5
Geometric Mean	Chipped	205.02	6.30	0.031
	Unchipped	475.50	8.69	0.018
Median	Chipped	239.72	4.87	0.026
	Unchipped	596.70	10.41	0.018
Range	Chipped	22-610.68	1.42-30.97	0.015-0.064
	Unchipped	13.6-1119.48	2.29-19.58	0.007-0.170
Standard Deviation	Chipped	163.72	9.30	0.017
	Unchipped	265.72	8.00	0.042

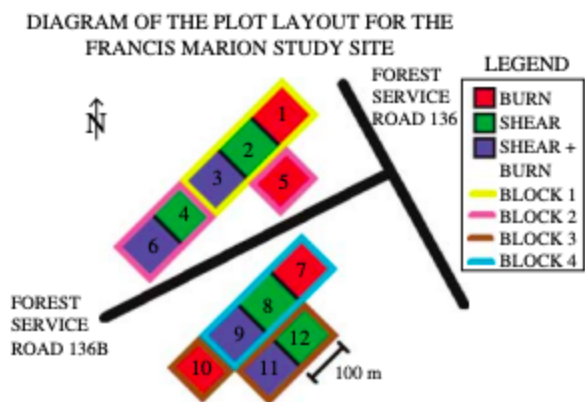


Figure 3.1 FMNF Map (Source: Naeher et al. 2006)

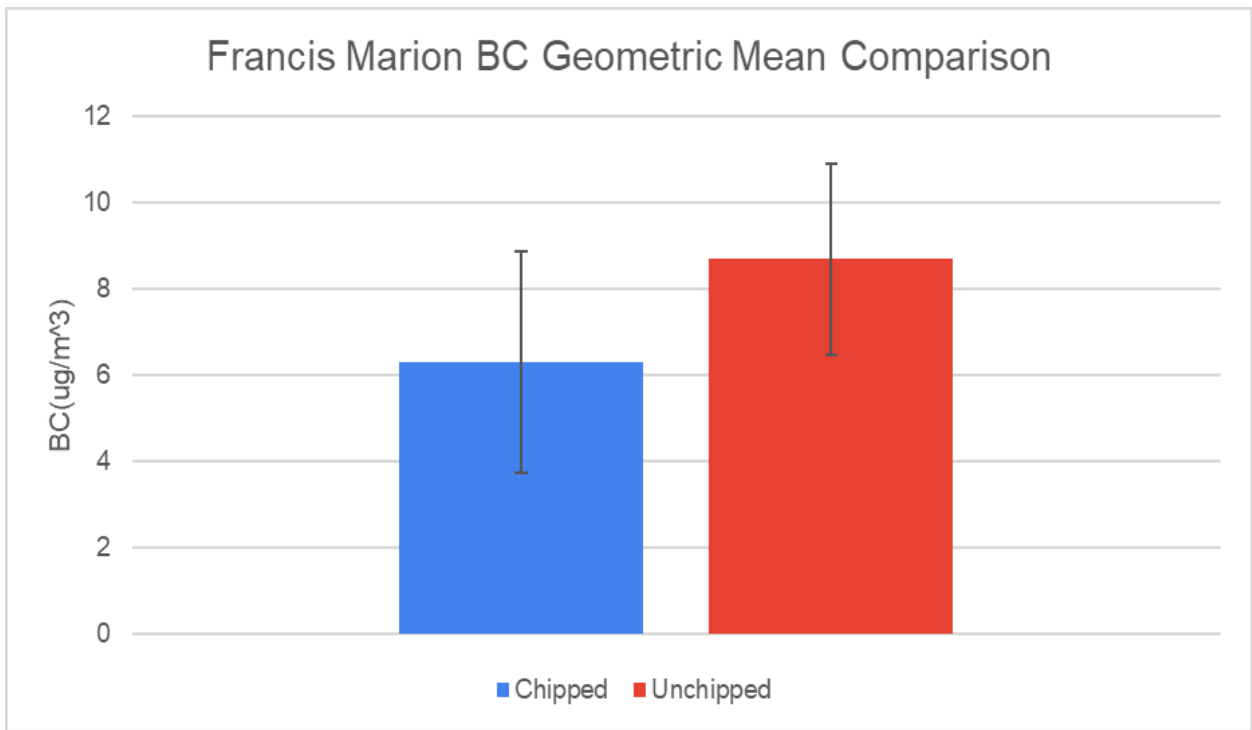


Figure 3.2. Comparison of BC Geometric Means (+/- Std Err)

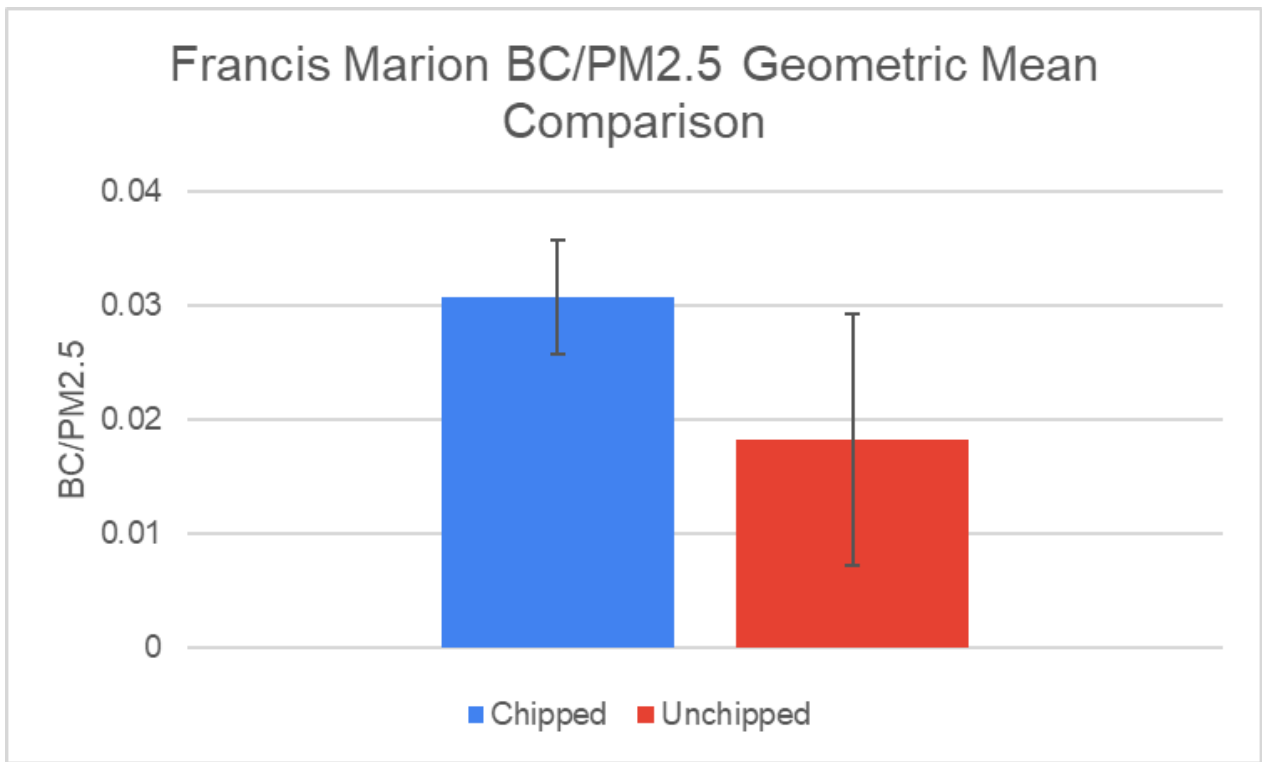


Figure 3.3. Comparison of BC/PM2.5 Geometric Means (+/- Std Err)