OCCUPATIONAL EXPOSURE TO WOODSMOKE AND ASSOCIATED CHANGES IN LUNG FUNCTION AND BIOMARKERS OF OXIDATIVE STRESS AMONG WILDLAND FIREFIGHTERS

by

OLORUNFEMI TOSIN ADETONA

(Under the Direction of LUKE P. NAEHER)

ABSTRACT

Objectives: To: (1) characterize exposure of wildland firefighters to particulate matter with aerodynamic diameter less than 2.5 microns ($PM_{2.5}$) and Carbon Monoxide (CO) in woodsmoke; (2) assess the utility of the relationship between exposures to $PM_{2.5}$ and CO in woodsmoke as a tool for exposure control; (3) investigate the effects of occupational woodsmoke exposure on lung function among wildland firefighters and (4) investigate the effects of occupational woodsmoke exposure on oxidative stress by using urinary 8-hydroxy-2'-deoxyguanosine (8-OHdG) and malondialdehyde (MDA).

Methods: Time integrated and real-time $PM_{2.5}$ and CO were monitored in the breathing zones of wildland firefighters working at prescribed burns. Concurrent lung function measurements and urine samples for analysis of biomarkers of oxidative stress were also collected from the firefighters pre- and post-workshifts. Linear mixed effect models were used to estimate the correlation between workshift average exposures of the firefighters. Across shift changes in lung function and biomarkers of oxidative stress and the effect of cumulative exposure on lung function were also analyzed using linear mixed effect models.

Results: Although geometric means of particulate matter exposure were below occupational exposure standards, they were at least 8 times the ambient air quality standard in the United States. Workshift averages of $PM_{2.5}$ and CO were well correlated with each other (ρ_{est}=0.79, $p<0.01$). There were no across shift changes in lung function and biomarkers of oxidative stress. However, each additional day of exposure was estimated to be associated with declines of 24ml in pre-shift FVC and 24ml in pre-shift FEV_1 ($p<0.01$). There was also evidence that across shift change in creatinine corrected 8-OHdG in the firefighters depended on the length of firefighting career or age of the subject ($p<0.01$).

Conclusion: Wildland firefighters are exposed to elevated levels of $PM_{2.5}$. Although acute health response as measured by across shift changes in lung function and biomarkers of oxidative stress was not observed, there is evidence that cumulative exposure to woodsmoke may cause some longer term health effects.

INDEX WORDS: Woodsmoke, wildland firefighters, $PM_{2.5}$, carbon monoxide, spirometry, forced vital capacity (FVC), forced expiratory volume in 1 second (FEV_1), oxidative stress, 8-OHdG, MDA

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DEDICATION

To my parents, Olufunke and Olalekan Adetona, for instilling a passion for learning from a very young age; I thank God you never stopped welcoming my questions. It’s been a long journey since then but I have carried both of you with me, and continue to be grateful that you personally tutored, and leafed through the pages of homework, newspapers and encyclopedias with me. You certainly started me on my way!

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CHAPTER 1

INTRODUCTION

The combustion of wood yields a complex mixture which is constituted in part by some potentially health damaging and environmentally harmful pollutants. Some of these include carbon monoxide (CO), aldehydes, polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs) and particulate matter (PM) (Naeher et al. 2007). Woodsmoke has been associated, with varying degree of evidence, with a wide range of health effects including lung function decline, asthma and respiratory symptoms, upper respiratory illnesses, chronic bronchitis and chronic obstructive pulmonary disease (Gaughan et al. 2008a; Kurmi et al. 2010; Naeher et al. 2007; Orozco-Levi et al. 2006a).

Globally a substantial number of people are exposed to woodsmoke. Wood, which is a major source of energy in many parts of the world is combusted for heating and cooking (Fullerton, Bruce, and Gordon 2008). It is also combusted during wildfires of various intensity and sizes, and intentionally in prescribed burns for land management reasons. Consequently, there are environmental and occupational exposures to different levels of woodsmoke for varying length of times. Health effects have been studied to a limited degree among populations who are transiently or chronically exposed to elevated levels of woodsmoke. These often include populations who have high level indoor exposure to CO and PM in developing countries, where wood and other biomass fuels remain the primary source of energy used for cooking and/or residential heat supply for one-third of the world's population (Fullerton et al. 2008).

Similarly, wildland firefighters are often exposed to elevated levels of woodsmoke due to the nature of their jobs as frontline defense against wildfires, and in the management of the landscape using prescribed fires. According to the National Interagency Fire Center (NIFC), there were 71,971 fires covering almost 3.5 million acres of forests, and wildland firefighters employed by federal and state agencies worked at 16,882 prescribed burns covering almost 2.5 million acres of forests in the United States in 2010 (NIFC, 2011). The United States Federal Government alone employs about 15,000 wildland firefighters each year (Gaughan et al. 2008a), and it is estimated that tens of thousands more work annually across the country (Harrison, Materna, and Rothman 1995). However, no wildland firefighting occupational exposure limits (OEL) exist for the prime pollutants in woodsmoke, especially particulate matter (PM). Older studies of occupational exposure in Western United States have shown that the chief inhalation hazards in woodsmoke to wildland firefighters are aldehydes, carbon monoxide (CO), and PM (Materna et al. 1992; Reinhardt and Ottmar 2004).

Although few studies address the issues, increasing attention has recently been paid to occupational woodsmoke exposure and consequent health effects among wildland firefighters. In 2010, the United States Forest Service (USFS) created an expert panel tasked with developing occupational exposure limits for wildland firefighters. However, previous exposure and health studies have largely been conducted in Western United States, and data are lacking for other regions of the United States where factors such as vegetation and climate, which may impact on exposure are different. There is also a need for a better understanding of the relationship between exposure to PM and other pollutants in woodsmoke, especially CO. This relationship may be useful for managing exposure among the firefighters. Furthermore, health end-points in studies of the effects of woodsmoke exposure among wildland firefighters have been limited to respiratory symptoms and lung function changes. Thus, there is need to broaden the investigation of possible health effects and to include other health end-points which could be used as indicators of potential chronic effects of cumulative exposure.

Therefore, this research dissertation reports the results of occupational exposure studies that were conducted in a Southeastern United States forest among a wildland firefighter crew working at prescribed burns. Prescribed burn is an important land management strategy in the region, and is used to manage fuel load and create conducive habitats for wildlife. It is estimated that as much as 6 to 8 million acres of land in Southern United States are treated with prescribed burns each year (Naeher et al. 2006). Studies were conducted during the dormant winter burn seasons of 2003-05 and 2011 to characterize the exposure of wildland firefighters to $PM_{2.5}$ in woodsmoke, identify the factors that affect the exposures of the firefighters, and determine the relationship between $PM_{2.5}$ and CO both as exposures averaged over the workshift, and in real time. The 2003-05 study is presented in Chapter 3. The 2011 study was in part designed to answer questions arising from the earlier 2003-05 study because the time integrated $PM_{2.5}$ exposure data collected during the period proved inadequate for analyzing the effect of firefighter job task on exposure. The results of the 2011 exposure study are therefore presented last in this dissertation in Chapter 6.

Additionally, the effect of woodsmoke exposure on lung function was investigated. An older study had observed across shift declines in lung function among wildland firefighters (Betchley et al. 1997a). However, measurements of lung function were restricted to the days when the firefighters worked at a forest fire (burn days), and the observed across shift changes were not compared to the days when the firefighters did not work at a fire (non-burn days). This approach could have led to the results being confounded by the natural circadian pattern associated with lung function (Borsboom et al. 1999). Consequently, a study was conducted to compare changes in lung function on burn days to changes on non-burn days. The effect of cumulative woodsmoke exposure on lung function during the burn season was also investigated. The results of this study are presented in Chapter 4.

Lastly, we investigated oxidative stress as a possible health end-point for woodsmoke exposure among firefighters using urinary biomarkers, 8-OHdG and MDA. In-vitro and animal studies show that particles in woodsmoke are capable of inducing oxidative stress in different cell lines and animal models (Danielsen et al. 2010; Danielsen et al. 2009). Furthermore, results of human experiments indicate that woodsmoke may induce oxidative stress in humans (Barregard et al. 2008a; Danielsen et al. 2008). It has also been shown that woodsmoke particles contain free radicals and are capable of generating reactive oxygen species (ROS) in cells (Leonard et al. 2000). However, outside of chamber experiments, there has been no study of oxidative stress among the general population even though elevated woodsmoke exposure situations exist. We therefore investigated the across shift changes in urinary 8-OHdG and MDA among wildland firefighters working at prescribed burns, and the study along with its results are presented in Chapter 5 of the dissertation.

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CHAPTER 2

LITERATURE REVIEW

WOODSMOKE EXPOSURE

Globally, a substantial number of people are exposed to woodsmoke in different environments characterized by different levels, varying duration and frequency of exposure. This include people, particularly women and children in developing countries who experience indoor exposure to elevated levels of woodsmoke due to the combustion of wood in homes (Fullerton et al. 2008). Most rely on inefficient stoves which produce high levels of pollution, especially particulate matter, due to inefficient combustion (Albalak et al. 2001). These exposures account for a considerable portion of the global disease burden with the more vulnerable sub-populations of children and women being the more exposed (Fullerton et al. 2008). It has been estimated that indoor air pollution in developing countries, of which wood combustion is a major contributor, is responsible for 2.7% of the global burden of disease (Rehfuess, Mehta, and Prüss-Üstün 2006).

Efforts to reduce exposure among this population has largely been based on woodstove intervention programs geared towards providing homes in these parts of the world with stoves that have higher combustion efficiency. Most recently in 2010, a public-private venture, the "Global Alliance for Clean Cookstoves", was launched in the United States to address the problem of indoor woodsmoke exposure in developing countries. Many of the past and ongoing woodstove intervention efforts have been the focus of many exposure assessment and health studies with the objective of measuring the efficiency of pollution reduction in terms of personal exposure to and room concentrations of $PM_{2.5}$ and CO, and the impact of such interventions on various health effects (Clark et al. 2009; Cynthia et al. 2008b; Díaz et al. 2007; Harris et al. 2010; Pennise et al. 2009; Romieu et al. 2009; Smith et al. 2007).

Woodsmoke due to residential combustion of wood is also responsible for exposure to air pollutant in parts of the developed temperate regions of the world where a relatively large number of people still rely on wood as the source of heat supply during the colder months of the year. Hence, exposures in these parts of the world are seasonal, and outdoor concentrations of pollutants, particularly PM, can be heavily impacted by residential wood combustion during the winter in these parts of the world (Favez et al. 2009; Glasius et al. 2006; Krecl et al. 2008; Maykut et al. 2003). However, exposures in such situations are much lower than those reported for indoor exposures in developing countries.

Seasonal general population exposures to pollutants from woodsmoke also occur during the wildfire season in parts of the world. Wildfire events have been associated with various acute health effects, and depending on their size, sometime affect a substantial number of people. Millions of people were affected by the Southeast Asia wildfires of 1997 (Heil and Goldammer 2001), with pollution from them being transported hundreds of miles away from their origins. However, wildland firefighters are usually the most directly exposed group during wildland fires. Their immediate proximity to fires during wildfire events, and also at prescribed burns, exposes them to elevated levels of woodsmoke. Therefore, they are a useful population for determining the health effects associated with woodsmoke exposure and the mechanisms of toxicity. While studying wildland firefighters is important towards controlling their exposure to woodsmoke, conducting research among them could also yield results relevant to exposures responsible for a sizeable portion of the global disease burden represented among the different population groups identified above.

Wildland Firefighters and Prescribed Burns

Wildland firefighters are primarily responsible for the suppression of wildfires. Often the first line of defense, wildland firefighters along with other resources are deployed to fight wildfires, usually for the purposes of protecting lives and properties. This function has increasingly become important as the wildland-urban interface continues to expand (Radeloff et al. 2005; Theobald and Romme 2007). Wildland firefighters also engage in prescribed burns. Prescribed burns involve the deliberate application of fire as a land management tool for improving forage value of the forests, and reducing wildfire hazard and competing vegetation (Reinhardt 1991). Annually in the United States, prescribed burns are applied by tens of thousands of firefighters to millions of acres of land; as much as 6 to 8 million acres are treated with prescribed burns each year in the southern part of the country alone (Naeher et al. 2006).

While conducting prescribed burns, wildland firefighters are assigned different tasks which may affect their level of exposure to woodsmoke. The major task groupings include the following:

Lighting: lighting involves fuel ignition. Lighting is often done on foot and by hand using a drip torch which usually contains a gasoline-diesel (ratio 1:3) fuel mixture. Lighting may sometimes be achieved aerially with the use of helicopters with the aid of a “helitorch”, a giant drip torch hung beneath the helicopter, or “ping-pong” balls which are plastic spheres containing potassium permanganate ($KMnO_4$) injected with ethylene glycol.

Holding: holding involves the maintenance of fires within defined burn boundary lines. Holding may be done on foot, on a mule, which is otherwise known as multifunctional utility/logistics and equipment vehicle, or with the aid of a four-wheel drive vehicle depending on the terrain.

Mop-up: mop-up is the extinguishing of smoldering fire after the major burning phase. Mop-up may also be done on foot, on a mule or with the aid of a four-wheel drive vehicle.

Direct attack: direct attack is the quick extinguishing of fire that jumps or spots outside the defined burn boundary.

The tasks monitored in studies reported in this document include lighting, holding and mop-up, but not direct attack. Other factors which could in theory affect the level of exposure of the firefighter to woodsmoke at prescribed burns include temperature, humidity, wind speed, size and duration of burn, type of vegetation, fuel moisture, and fuel load.

Wildland Firefighter Occupational Exposure to Woodsmoke

While wildland firefighters are potentially exposed to elevated levels of woodsmoke, they typically conduct their jobs with little or no protection against inhalation hazards. Available respirators do not provide protection against CO or when they do, as in the case of self-contained breathing apparatus (SCBA), are impractical for most firefighting tasks (Reinhardt and Ottmar 2004). Consequently, wildland firefighters seeking to reduce their exposures often rely on cotton cloth bandanas which are not effective in protecting against PM exposure (Naeher et al. 2007). The pore size of such bandanas, used by firefighters at a wildfire in Yosemite National Park was 100 µm, thus affording no protection even against inhalable particles (PM_{10}) (Reh, Letts, and Deitchman 1994). Although smoke exposure among wildland firefighters had long been recognized as an occupational issue, it is only within the last forty years that such exposures have become a subject of systematic investigation (Reinhardt et al., 1997). However, research in this area remains limited and gaps still remain in understanding wildland firefighter occupational smoke exposures. Most of the research that has been conducted on the subject was done in Western United States, while data for other regions of the country remains limited.

The array of pollutant in woodsmoke that has been studied in occupational exposure among wildland firefighters includes CO, total and respirable particles, silica, aldehydes, benzene, and PAHs (Materna et al. 1992; Reinhardt and Ottmar 2004; Reisen and Brown 2009). One study also researched exposure to herbicides at prescribed burns in Georgia, United States (McMahon and Bush 1992). The consensus from these studies is that CO and PM are the chief inhalation hazard to wildland firefighters. Overall means of time weighted average (TWA) exposures usually do not exceed the Occupational Safety and Health Administration (OSHA) permissible exposure limits (PEL) or the usually lower American Conference of Government Industrial Hygienists (ACGIH) threshold limit values (TLV) for exposure over an 8-hour work period. However, these limits may be exceeded for certain subjects, with exposure standards of CO and PM being the most frequently exceeded (Reinhardt and Ottmar 2004). Additionally, transient exposures above recommended and regulation short term exposure or excursion limits and ceiling limits were observed during firefighting (Reinhardt and Ottmar 2004). These peak exposures may be important for the study of health effects of occupational woodsmoke exposure among wildland firefighters.

A study of wildland firefighters at wildfires in California, Idaho, Montana and Washington measured exposures of wildland firefighters to aldehydes, CO, carbon dioxide (CO_2) and $PM_{3.5}$ at initial attack and project wildfires (Reinhardt and Ottmar 2000). Exposures were higher at project wildfires with average workshift and fireline TWA CO exposures at these fires of 2.8 ppm and 4.0 ppm respectively. While no CO exposure at the project fires exceeded the PEL of 50 ppm, some firefighters experienced exposures above the TLV (25 ppm), with maximum exposures of 31 ppm and 39 ppm for the workshift and fireline respectively. Also, a few peak exposures were briefly above the ceiling limit of 200 ppm. Average TWA respirable particle exposure measured over the workshift and at the fireline were 500 $\mu g/m^3$ and 720 $\mu g/m^3$ respectively. None of the firefighter at these fires had a TWA $PM_{3.5}$ exposure in excess of the PEL (5000 $\mu g/m^3$) or the TLV (3000 $\mu g/m^3$). It should be noted however that these occupational standards are many times the more recently developed United States Environmental Protection Agency's (USEPA) national ambient air quality standards (NAAQS) which are 9 ppm for CO, and 35 $\mu g/m^3$ for $PM_{2.5}$ over a 24-hour period. Similar levels of exposure were reported for a study among the Type I hotshot crews deployed to fight the Thompson Creek fire in the Gallatin National Forest in 1991. Average CO exposures on the three days of monitoring were 1.6, 6.9, and 6.2 ppm, while average $PM_{3.5}$ exposure was 370 $\mu g/m^3$, and a maximum of 4300 $\mu g/m^3$ (Kelly 1992). Higher exposures were reported for wildfires in northern California with mean TWA $PM_{3.5}$ of 1750 $\mu g/m^3$ measured at the fireline during mop-up activities (Materna et al. 1992). Exposures reported for Australian firefighters working at wild bushfires are within the range of exposures noted above (Reisen and Brown 2009). Carbon monoxide content in end-exhaled breath and the blood have also been used to assess occupational wildland firefighter exposure to woodsmoke. Significant cross-shift changes in carboxy-hemoglobin (COHb) were observed, while blood COHb levels above the 5 percent lower acute health effect limit were measured in some firefighters (Reinhardt and Ottmar 1997).

In the most comprehensive wildland firefighter occupational exposure data presented in the literature (Reinhardt and Ottmar 2004), higher levels of exposures were experienced by firefighters working at prescribed burns compared to those experienced at wildfires in Western United States. Personal TWA exposures at prescribed burns were higher by 25% or more for all pollutants measured except CO_2 and total particulate. Results also indicate that exposure may vary by the job task of the firefighters (Reinhardt and Ottmar 2004). Firefighters who are engaged in holding during prescribed burns seem to experience higher levels of exposure as the nature of the task places them more often in the path of the smoke emanating from the burns. Wind speed was also observed to be positively correlated with exposure for fighfighters doing direct attack at prescribed burns.

Importantly for exposure control, results show that exposures of firefighters at wildfires and prescribed burns to different pollutants in woodsmoke are well correlated with each other. The r^2 values for regression equations between pairs of pollutants ranged between 0.63 and 0.86 in studies conducted in Western United States (Reinhardt and Ottmar 2004). This implies that one pollutant in woodsmoke might be used as a surrogate to monitor the exposure of firefighters to woodsmoke or other pollutants in the mixture. Profiles of real time exposure data may also be important for exposure control. Results indicate that TWA fireline and workshift exposures may be dominated by transient peaks. In a pilot project which was designed to assess the utility of real time monitors for controlling exposure, and was conducted as part of the 2003-05 exposure study reported in this document, concentrations above 1000 $\mu g/m^3$ contributed 16% to 74% of the exposure to $PM_{2.5}$ accounting for just 3% to 22% of exposure time (Edwards et al. 2005). One possibility for managing exposure would be to keep firefighters out of the smoke or use respiratory protection temporarily during such periods of elevated exposures. This approach could be implemented with the aid of real time monitors equipped with alarms set to go off at certain thresholds.

Although studies such as the ones presented above are available, gaps still remain in understanding the occupational exposure of wildland firefighters to woodsmoke. Thus this project was designed to achieve the following objectives:

1. Provide exposure data regarding exposures of wildland firefighters in a region different from Western United States where most of the studies in the literature have been conducted. We carried out the studies in this document at a forest in Southeastern United States among firefighters conducting understory prescribed burns in the natural fuels that are common in Southeast United States.

2. Investigate the exposure of firefighters to PM in real time. Most of the available data is for PM exposure aggregated over at least 15 minute period. Real time PM data would also be useful in further exploring the contributions of transient peak exposures to workshift TWA exposures.

3. Investigate the relationship between exposures to CO and PM in real time. Although previous results had shown that exposures of wildland firefighters to both pollutants are related when averaged over the whole workshift, investigating their relationship in real time could be important for exposure control since both pollutants may have more variation associated with them over smaller spatial and temporal resolutions.

EPIDEMIOLOGY OF WOODSMOKE EXPOSURE

Research into the effects of woodsmoke exposure among the general population has largely been conducted by examining three different exposure situations. These include the investigation of the associations between cardio-respiratory morbidities and pollutant levels in ambient air with substantial contributions from wood combustion (Johnston et al. 2007; Morgan et al. 2010; Sarnat et al. 2008; Schreuder et al. 2006); changes in the incidences of cardio-respiratory symptoms and diseases during big wildfires (Duclos, Sanderson, and Lipsett 1990; McGowan et al. 2002; Moore et al. 2006; Mott et al. 2002; Sorenson et al. 1999; Sutherland et al. 2005); and the health effect of woodsmoke exposure due to the residential combustion of wood, particularly in developing countries where such exposure is often elevated and chronic (Boy, Bruce, and Delgado 2002; Dennis et al. 1996; McCracken et al. 2007; Romieu et al. 2009). Measures of exposure in ambient air studies are based on PM concentrations measured by area monitors or estimated from source apportionment methods, or on concentrations of tracer substances/elements of sources of PM. In one study covering a 7-year period from 1995 to 2002, an inter-quartile range (IQR) increase in concentration of one day lagged total carbon – used as a tracer for "vegetative burning" – was associated with a 2% increase in respiratory emergency room visits (Schreuder et al. 2006). This translated to a 0.6% increase per $\mu g/m^3$ of woodsmoke particle mass. Association of total carbon with respiratory emergency room visits was higher during the winter months ("heating" season) with a 5% increase in the number of visits associated with an IQR increase in total carbon. Another ambient air study based on source apportionment methods also reported a positive association between same-day woodsmoke and biomass burning PM, and cardiovascular disease emergency department visits but not respiratory disease visits in Atlanta, GA (Sarnat et al. 2008). The association of particulate matter from these two sources with cardiovascular disease was consistent throughout the year, and biomass burning was primarily due to prescribed forest burns.

A study done in Sydney, Australia isolated days when ambient air PM was primarily derived from bushfires, and reported a 1.24% increase in hospital admissions for respiratory diseases for every same-day 10 $\mu g/m^3$ increase in bushfire PM. No association with cardiovascular diseases was found (Morgan et al. 2010). A positive association between ambient air PM_{10} concentration and hospital admissions for respiratory diseases was also found in another Australian study (Johnston et al. 2007). In Christchurch, New Zealand, where wood combustion during winter months was estimated to contribute ninety percent of the particulate air pollution, an IQR (14.8 $\mu g/m^3$) increase in a 2-day lagged PM_{10} was also associated with a 3.37% (95% CI 2.34–4.40) increase in hospital admission for respiratory diseases (McGowan et al. 2002), and a 1.26% increase in cardiovascular disease admissions. Summer PM_{10} levels in the Christchurch study were reported to be virtually constant and about one-quarter of winter PM_{10} levels.

Wildfire events have also been associated with increase in the incidences of various symptoms and diseases. The number of hospital visits and/or admissions during the wildfire event compared to corresponding referent periods in preceding and succeeding years is usually the metric of health effects used in these studies. A 10 $\mu g/m^3$ wildfire related $PM_{2.5}$ was associated with a 9.6% increase for persons of all ages in acute bronchitis admission and a 6.9% increase for persons 20-64 years old in chronic obstructive pulmonary disease (COPD) admission during wildfire events in southern California in October 2003 (Delfino et al. 2009). In an earlier study, increases in hospital visits for laryngitis, upper respiratory infections and sinusitis were associated with a 1987 wildfire event that consumed more than 600,000 acres of lands in California (Duclos et al. 1990). The absolute number of hospital visits due to respiratory problems increased by 52% among residents of Hoopa Valley National Indian Reservation in northwestern California during what was then described as the fifth largest wildfire in the United States in August to November 1999 compared to the corresponding period in the previous year

(Mott et al. 2002). The occurrence of respiratory disease visits as a proportion of total hospital visits also increased during the wildfire.

Similar results to those referenced above have been reported for the 1997 Southeast Asia forest fires. According to one estimate, haze from the fires affected an estimated 70 million people with an estimated 20 million being exposed to PM_{10} concentrations above the USEPA's NAAQS of 150 $\mu g/m^3$. Emmanuel (2000) reported a 30% increase in hospital visits for "haze-related conditions" with an increase from 50 $\mu g/m^3$ to 150 $\mu g/m^3$ during the wildfire period being significantly associated with increases in hospital visits due to rhinitis (26%), asthma (19%) and upper respiratory tract illness (12%) (Emmanuel 2000). High pollution due to the fires defined as $PM_{10} > 210$ $\mu g/m^3$ was also associated with increased total and non-traumatic mortality in the 65-75 years old age group in Kuala Lumpur, Malaysia (Sastry 2002). Estimates were not available in this particular study for mortality due specifically to cardio-respiratory diseases because of insufficiencies in the data. Increase in systemic inflammation measured as elevation in band neutrophils as a percentage of total polymorphonuclear (PMN) leukocytes (Tan et al. 2000) and increases in serum pro-inflammatory cytokines (van Eeden et al. 2001) among a group of thirty healthy volunteers (19-24 years) were observed during the Southeast Asia forest haze compared with the immediate post-haze period.

Indoor exposure to woodsmoke, especially in developing countries, accounts for a substantial proportion of the global health burden (Fullerton et al. 2008). The residential use of biomass fuel, with wood being the most commonly used, has been associated with increase in the incidences of various respiratory diseases including pneumonia, COPD and tuberculosis; low birth weight, cataracts and all cause mortality in children and adults (Fullerton et al. 2008; Naeher et al. 2007). Women and children have been the focus of most of the research about the subject. This is due to the fact that they tend to spend more time indoors. In a randomized woodstove intervention study, women who reported using only the newly improved stove (Patsari) had less decline in lung function with a mean decline in forced expiratory volume (FEV_1) of 31 ml over the one year follow-up period compared with women who used the traditional open fire woodstoves (62 ml) (Romieu et al. 2009). Women who used the new stove were also less likely to report having respiratory symptoms during the follow-up period.

Residential combustion of wood has also been linked to chronic respiratory diseases. In a case-control study conducted in Bogota, Colombia, women who reported using wood for cooking had an odds ratio (OR) of 3.92 (CI: 1.7-9.1) for being a case with obstructive airway disease (Dennis et al. 1996). In another case-control, women recruited from a hospital in Spain and who reported to have cooked with wood or charcoal (mean exposure time = 16 years) were more likely to be cases with COPD (OR: 4.5; CI: 1.4-14.2) (Orozco-Levi et al. 2006a). Prolonged woodsmoke exposure has also been linked with pulmonary arterial hypertension (Sandoval et al. 1993) and lung cancer in exposure periods exceeding 50 years (Hernandez-Garduno et al. 2004).

The results of epidemiological studies among the general population are quite consistent for respiratory effects. Although, there is paucity of data, there are also indications of potential impact of woodsmoke exposure on cardiovascular diseases (Johnston et al. 2007; Sarnat et al. 2008).

TOXICOLOGY OF WOODSMOKE EXPOSURE

In-vitro and Animal Studies

Animal and in-vitro studies of the effect of woodsmoke exposure like other laboratory studies suffer from the disadvantage of being inexact models of the interaction between the pollutant and humans, and hence the difficulty in extrapolating results to humans. Furthermore, the nature of woodsmoke as a mixture makes it more difficult to study, and most studies of its effects have rather focused on singular components. However, laboratory studies are helping to elucidate the mechanism of toxicity for woodsmoke. Woodsmoke PM and its extracts have been the focus of most in-vitro studies, possibly due to the fact that fine particles are thought to be the best single indicators of the health effects of most combustion sources (Naeher et al. 2007). The mechanism of toxicity by particulate matter is hypothesized to involve the generation of reactive oxygen species (ROS), oxidative stress, and inflammation (Li et al. 2002); thus research into the health effects of wood combustion generated PM on these health points have been researched in-vitro.

Wood combustion derived PM contain free radicals and is capable of generating hydroxyl radical in Fenton-like reactions in acellular environments; woodsmoke PM and its extracts are capable of inducing the production of hydrogen peroxide (H_20_2) and other ROS in different airway cell lines (Lee et al. 2008; Leonard et al. 2007; Leonard et al. 2000; Liu et al. 2005). Production of ROS within the cell could trigger oxidative stress and cytotoxicity, and cause cell proliferation and apoptosis as shown in rat alveolar epithelial type II cell and human lung endothelial cell lines (Lee et al. 2008; Liu et al. 2005). Results of in-vitro studies show that exposure to woodsmoke PM induces oxidative stress in the cell resulting in lipid peroxidation and DNA damage.

Danielsen et al. (2008) report that there was an increase in both strand breaks and formamidopyrimidine DNA glycosylase sites in human A549 lung epithelial and THP-1 monocytic cell lines after exposure to woodsmoke particles (Danielsen et al. 2009). Their results show that woodsmoke PM collected from a conventional Norwegian woodstove generated more DNA damage than traffic PM per unit mass in both cell lines; they explained that this might have been due to the high level of PAHs in the woodsmoke PM. Cell toxicity or viability was not statistically different between exposed and control cells in the Danielsen et al. (2008) study, or in another study conducted by the same research group using ambient PM in addition to woodstove generated PM (Danielsen et al. 2011). However, other studies have shown that woodsmoke PM could induce cell toxicity (Jalava et al. 2006; Jalava et al. 2010; Kocbach et al. 2008). The differences between the results of these studies with regards to cell toxicity may be explained in part by the differences in the assays used, cell lines, exposure times, and physicochemical properties of the particles. Exposure to woodsmoke PM extracts also impact antioxidant systems in cells of the airways causing the upregulation of antioxidant enzymes such as heme oxygenase-1 (HO-1) (Lee et al. 2008; Liu et al. 2005).

In addition to the above mentioned effects, in-vitro studies show that woodsmoke particles have pro-inflammatory potential similar to particles derived from other combustion sources. Exposure to woodsmoke PM increased pro-inflammatory cytokines – tumor necrosis factor (TNF-α), and interleukins IL-6 and IL-8 which is a chemo-attractant for inflammatory cells – in a co-culture of THP-1 and A549 cells (Kocbach et al. 2008). The organic fraction of the particles accounted for the majority of the cytokine released. The inflammatory potential of the particles may also be affected by the combustion condition.

Woodsmoke exposure induced oxidative stress and inflammatory responses have also been observed in animal models. Thiobabituric acid reactive substances (TBARS), which is a surrogate measure for malondialdehyde (MDA) – a product of lipid peroxidation – was increased in plasma and lung tissues of male sheep 48 hours after exposure to cooled western pine bark smoke via mechanical inhalation compared to controls (Park et al. 2004). Similarly, lung TBARS levels were increased in scald or sham burn rats exposed to the same type of smoke (Dubick et al. 2002). Additionally, woodsmoke PM derived under low combustion conditions increased expression levels of HO-1 in the lungs of Fischer 344 rats exposed by intratracheal instillation to approximately 125 μg of the particles in a study by Danielsen et al (Danielsen et al. 2010). However, there was no evidence of oxidative DNA damage in the lung after exposure to ambient air particles dominated by woodsmoke PM, and woodsmoke PM generated by a woodstove under low and high oxygen combustion.

The Danielsen et al. study also investigated inflammatory responses to woodsmoke PM exposure by intratracheal instillation. The number of cells, consisted mostly of macrophages, did not increase in the bronchoalveolar lavage fluid (BALF) collected from the exposed rats 24 hours after the exposure. However, the number of neutrophils in BALF in the exposed rats increased compared to the controls. In addition, exposure to the woodsmoke PM generated under low oxygen condition increased the gene expression of macrophage inflammatory protein-2 (MIP-2) which is a chemoattractant involved in the recruitment of neutrophils in the lung. Recruitment of neutrophils into the lungs without an increase in the total number of cells was also observed in mice instilled with 10 or 25 μg of wildfire $PM_{10-2.5}$ (Wegesser, Pinkerton, and Last 2009). The shift towards neutrophils in the BALF was more drastic for the mice compared to the rats in the Danielsen et al. study. Since there was an increase in the number of neutrophils but no change in the total cell count, it was suggested that woodsmoke PM exposure was particularly toxic to macrophages, or that the wildfire $PM_{10-2.5}$ created a condition which made it more difficult to extract macrophages from the lung by lavage due to increased adherence of macrophages to the alveolar surface. The effect of 6 month-subchronic (6 hours/day, 7 days/week) hardwood smoke exposure on BALF pro-inflammatory cytokine in CDF (F-344)/CrlBR rat was complex and inconsistent with regards to the sex of the rat and the concentration of exposure (Seagrave et al. 2005). However, the results could have been affected by the ability of carbonaceous particles to bind cytokines.

In summary, these studies show that exposure to woodsmoke or its component(s), especially PM, could be harmful; that such exposure could induce oxidative stress and inflammatory responses. However, PM is not the only harmful component in woodsmoke. For example, acute exposure to elevated levels of CO in woodsmoke during firefighting could cause headache, fatigue, dizziness and neurological effects, all of which could result in the deterioration of performance at work (Raub et al. 2000). Occupational exposures to other compounds such as Benzene and aldehydes among firefighters are mostly below occupational standards (Reinhardt and Ottmar 2004). Exposure to aldehydes may be important because they are respiratory irritants and their effect would be additive to that of other irritants in woodsmoke. Woodsmoke also contains PAHs, some of which are known carcinogens (Naeher et al. 2007). While the International Agency for Research on Cancer (IARC) has classified indoor emissions from combustion of biomass fuel (mostly wood) as probably carcinogenic,(Danielsen et al. 2008) very few epidemiological studies have shown a link between woodsmoke exposure and lung cancer.

Human Experimental Studies

In addition to the understanding of the mechanisms of toxicity, human experiments, when they can be done offer the advantage of representing more closely human exposure with regards to the route of exposure, and the ability to investigate the effects of whole mixtures rather than singular components. They also help to verify the relevance to humans of the biological responses observed in in-vitro and animal models. Unsurprisingly however, very few human woodsmoke exposure experiments have been conducted. Most of the results reported in the literature are from a chamber study which investigated the effects of woodsmoke exposure on multiple biological markers including those of oxidative stress, inflammation and pneumotoxicity (Barregard et al. 2006). The study consisted of 13 subjects who were exposed to woodsmoke (240–280 μg/m3) and clean air in a chamber in two 4-hour sessions one week apart. Woodsmoke was generated by firing a hardwood/softwood (50/50) mixture in a stove.

Although serum IL-6 decreased after exposure to woodsmoke in this study, increases were observed for other markers of inflammation (Barregard et al. 2006). Serum amyloid A (SAA) was increased in subjects immediately, three hours, and the following morning after exposure to woodsmoke. There was no increase in SAA at corresponding times following exposure to clean air. SAA is an acute phase protein and a marker of inflammation. An increase in plasma Factor VIIIc, also a marker of inflammation, was observed the following morning after exposure, while an increase in the Factor VIIIc/von Willebrand Factor (VWF) ratio was observed at all sample collection time points after exposure. Factor VIIIc/VWF ratio is used as an indicator of unbound Factor VIIIc (Barregard et al. 2006).

Although, there was an increase in urinary excretion of 8-iso-prostaglandin2α the morning after exposure in the study, chance was adduced as an alternative explanation for the observation. However, MDA in exhaled breath condensate among subjects in the study was increased three hours and the morning after exposure in this study, leading the authors to conclude that the exposure caused signs of increased oxidative stress in the respiratory tract (Barregard et al. 2008a). The increase in the excretion of 8-oxo-7,8-dihydro-oxoguanine (8-oxoGua) and 8-oxo-7,8-dihydro-2-deoxyguanosine (8-oxodG) in urine 20 hours after exposure to woodsmoke did not reach statistical significance. Even so, there was a significant increase in the expression of the DNA repair enzyme, oxoguanine glycosylase 1 (hOGG1) in peripheral blood mononuclear cells of the subjects. 8-oxoGua in the DNA is removed by hOGG1 (Danielsen et al. 2008). In addition, serum Clara cell protein (CC16) was increased 20 hours after exposure to woodsmoke (Barregard et al. 2008a). Clara cell protein is secreted by the non-ciliated Clara cells in the bronchiolar epithelium. Its concentration in circulation reflects airway epithelial permeability, and has been used as a biomarker of lung injury due to exposure (Broeckaert et al., 2000).

In summary, results of this study indicate that acute woodsmoke exposure induces pulmonary oxidative stress and inflammation in humans. There was also sign of pneumotoxicity as indicated by the increase in serum CC16.

HEALTH EFFECT STUDIES IN WILDLAND FIREFIGHTERS

Although they are exposed to elevated levels of woodsmoke and thus present a human population base for understanding the acute and chronic health effects of woodsmoke exposure, epidemiological studies of wildland firefighters are limited. This is in part due to the relative lack of exposure data, and the difficulty associated with following wildland firefighters as subjects in epidemiological studies due to their high level of mobility, and the relatively high rate of turnover associated with the profession. The mean career duration for a wildland firefighter was estimated to be 8 years (Booze et al. 2004). However, interest in the health effects of occupational woodsmoke exposure among this sub-population has recently been increasing.

The most studied health end points for woodsmoke exposure among wildland firefighters are lung function and respiratory symptoms including cough, phlegm production, wheeze, sore throat, and eye and nose irritation. In a cross-sectional study conducted in Sardinia, Italy, average forced expiratory volume in 1 second (FEV_1), ratio of FEV_1 to forced vital capacity (FEV_1/FVC), forced expiratory flows (FEF_{25}, FEF_{50}, FEF_{75}), and respiratory volume (RV) of 95 wildland firefighters were lower compared with those of 51 policemen working mostly in rural areas within the same province (Serra, Mocci, and Randaccio 1996a). Firefighters recruited for the study had not worked at a "big fire" in the month prior to lung function measurements, and the study was conducted before the most intense firefighting months. Small but significant declines in lung function across firefighting workshifts have been observed among wildland firefighters. Betchley et al. (Betchley et al. 1997a) reported pre-shift to mid-shift declines of 0.089 L, 0.190 L, and 0.439 L/sec and pre-shift to post-shift declined of 0.065 L, 0.150 L, and 0.496L/sec in FVC, FEV_1 and forced mid expiratory flow (FEF_{25-75}) respectively. The declines were not associated with occupational exposure to PM in woodsmoke. Lung function pre- and post-shift was not measured on days the firefighters did not fight fires, and so exposure associated declines were not compared to non-exposure controls. Such comparison is important since lung function is known to undergo a diurnal pattern (Borsboom et al. 1999; Troyanov et al. 1994). Moreover, some studies did not observe significant cross-shift declines in lung function in association with woodsmoke exposure (Gaughan et al. 2008a; Swiston et al. 2008).

Declines of 0.033 L, 0.104 L and 0.275 L/sec from pre- to post-fire-season were observed for FVC, FEV_1, and $FEF_{25\text{-}75}$ respectively in the Betchley et al. studies. Similar results have been reported by others (Liu et al. 2005; Rothman et al. 1991a). In one of these studies, declines in FVC and FEV_1 were associated with the hours of recent firefighting activities (Rothman et al. 1991a). In contrast, Letts et al. (Letts et al. 1991), in a health survey of 78 wildland firefighters in Southern California, reported non-significant cross-seasonal changes for FVC and FEV_1, no changes in the prevalence of symptoms, and no association between changes in these health responses and measures of exposure. They however reported significant cross-seasonal declines in $FEF_{25–75}$ and FEV_1/FVC. The authors also indicated that the survey had been conducted during a season with an atypical low number of firefighting hours. Declines observed from pre- to post-fire-season recovered during the off-season in studies where the relevant comparisons were made (Betchley et al. 1997a; Gaughan et al. 2008a). Increased airway hyper-responsiveness and prevalence of symptoms across the firefighting season have also been observed among wildland firefighters (Liu et al. 2005; Rothman et al. 1991a).

Other health end points have only recently been studied among wildland firefighters. Granulocytes and fraction of particulate inclusion-positive macrophages increased in the sputum of subjects recruited from among firefighters from the British Columbia Forest Service from pre- to post-firefighting woodsmoke exposure (Swiston et al. 2008). In addition, pro-inflammatory cytokines, IL-6 (from 0.82 ± 0.12 to 1.89 ± 0.43 pg/ml) and IL-8 (from 14.02 ± 3.48 to 45.03 ± 8.32 pg/ml) in the serum; total white cell, PMN, and band cell counts in the blood increased from pre- to post-firefighting woodsmoke exposure. These results indicated that woodsmoke exposure induced both pulmonary and systemic inflammation among the firefighters. The association of increases in sputum and nasal lavage myeloperoxidase (MPO) and eosinophilic cationic protein (ECP) with increased post-fire exposure symptom score among the members of two type I hotshot crews from the National Park Service also indicates that woodsmoke exposure from wildfires may induce airway inflammation (Gaughan et al. 2008a).

In summary, results of the studies referenced above indicate that occupational woodsmoke exposure could induce pulmonary effects among wildland firefighters. However, research in this area is limited and inadequate. Studies of other acute health end-points such as oxidative stress are rare or totally lacking. Similarly, possible chronic effects of occupational woodsmoke exposure among wildland firefighters have not been studied, at least partly due to the difficulty that following this population of workers would involve. In addition to studying the effects of lung function in a study presented in this dissertation, the possibility of occupational woodsmoke exposure induced oxidative stress among wildland firefighters was explored. Measurement on non-firefighting days was incorporated into the design of the lung function study, in order to control for diurnal variation.

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CHAPTER 3

PERSONAL $PM_{2.5}$ EXPOSURE AMONG WILDLAND FIREFIGHTERS WORKING AT PRESCRIBED FOREST BURNS IN SOUTHEASTERN UNITED STATES[1]

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ABSTRACT

Introduction: This study represents an investigation of occupational exposure to wood and vegetative smoke in a group of 28 forest firefighters at prescribed forest burns in a southeastern US forest during the winters of 2003-05.

Methods: 203 individual person-day $PM_{2.5}$ and 149 individual person-day CO samples were collected during burn activities and 37 person-day $PM_{2.5}$ samples were collected during non-burn activities as controls. Time activity diaries and post-workshift questionnaires were administered to identify factors influencing smoke exposure and to determine how accurately the firefighters' qualitative assessment estimated their personal level of smoke exposure with discrete responses: 'none' or 'very little', 'low', 'moderate', 'high' and 'very high'.

Results: An average of 6.7 firefighters was monitored per burn with samples collected on 30 burn days and 7 non burn days. Size of burn plots ranged from 1-2745 acres (avg = 687.8). Duration of workshift ranged from 6.8-19.4 hrs (avg = 10.3 hrs) on burn days. Concentration of $PM_{2.5}$ ranged from 5.9-2673 $\mu g/m^3$ on burn days. Geometric mean $PM_{2.5}$ exposure was 280 $\mu g/m^3$ (95% CL = 140, 557 $\mu g/m^3$, n = 177) for burn day samples, and 16 $\mu g/m^3$ (95% CL = 10, 26 $\mu g/m^3$, n = 35) on non-burn days. Average measured $PM_{2.5}$ differed across levels of the firefighters' categorical self-assessment of exposure ($p < 0.0001$): none to very little = 120 $\mu g/m^3$ (95% CL = 71, 203 $\mu g/m^3$) and high to very high = 664 $\mu g/m^3$ (95% CL = 373, 1185 $\mu g/m^3$); $p < 0.0001$ on burn days). Time weighted average $PM_{2.5}$ and personal CO averaged over the run times of $PM_{2.5}$ pumps were correlated (correlation coefficient estimate, r = 0.79; CLs: 0.72, 0.85).

Conclusions: Overall occupational exposures to particulate matter were low, but results indicate that exposure could exceed the American Conference of Governmental Industrial Hygienists'

(ACGIH) recommended threshold limit value (TLV) of 3 mg/m^3 for respirable particulate matter in a few extreme situations. Self-assessed exposure levels agreed with measured concentrations of $PM_{2.5}$. Correlation analysis shows that either $PM_{2.5}$ or CO could be used as a surrogate measure of exposure to woodsmoke at prescribed burns.

INTRODUCTION

Wildland firefighters are primarily responsible for wildfire suppression in wildlands including forests, grasslands and brush, but also engage in prescribed burning. Prescribed burns as opposed to wildfires are intentionally set by firefighters, and are used as a land management tool for improving forage value of the forests, reducing wildfire hazard and competing vegetation (Reinhardt 1991). They have become such a mandatory land management practice that as much as 6 to 8 million acres of land are treated with prescribed burns by land managers each year in Southern United States alone (Wade et al. 2000), and it is estimated that tens of thousands of firefighters work at these burns annually across the country (Harrison, Materna, and Rothman 1995).

Although very careful planning always precedes prescribed burns, wildland firefighters can be exposed to high levels of contaminants in woodsmoke. These include carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides, respirable particulate matter (RPM), total suspended particulates (TSP), polycyclic aromatic hydrocarbons (PAH), benzene, aldehydes and others (Naeher et al. 2007; Reinhardt and Ottmar 2000). Carbon monoxide, RPM, TSP and aldehydes have been identified as the chief woodsmoke exposure hazards among firefighters (Reinhardt and Ottmar 2000). Firefighters working at prescribed burns often work extended shifts (up to 18 hours) while exerting hard physical labor (Reinhardt and Ottmar 2000), and wearing no respiratory protection. Physical labor increases minute ventilation and total exposure of the respiratory tract to particles, gases, and vapors. Therefore firefighters are potentially at risk of serious acute and chronic health effects. Health effects that have been associated with occupational exposure to woodsmoke among wildland firefighters include reduced lung function, pulmonary and systemic inflammation (Betchley et al. 1997; Swiston et al. 2008).

Studies of exposures among wildland firefighters have mostly been conducted in the Western United States which has different vegetation and weather characteristics compared to other parts of the country. These studies show exposure to particulate matter and CO could exceed occupational health standards, and that exposures were higher among firefighters working at prescribed burns compared to those working at wildfires (Materna et al. 1992; Reinhardt and Ottmar 2000, 2004). Although conducted in a completely different environment, a study of exposure to vegetative smoke from bushfire at prescribed burns in Australia also point to the possibility of elevated exposure to RPM among wildland firefighters (Reisen and Brown 2009). We assessed occupational woodsmoke exposure in wildland firefighters working at prescribed burns in a Southeastern United States forest during the dormant (winter) burn seasons of 2003-2005. The objective of this study was to examine the association between particulate matter with median aerodynamic diameter of 2.5 microns ($PM_{2.5}$), and duration and sizes of burns, job tasks and weather variables to identify the factors which influence exposure. We also assessed whether the firefighters could qualitatively estimate their level of exposure.

METHODS

Study Location and Population

This study was conducted in the Southeastern United States at the Savannah River Site (SRS), which is a 198,000 acre National Environmental Research Park located in the southeastern coastal area of the U.S. The United States Department of Agriculture Forestry Service (USFS) manages the complex's natural resources including the forests which is composed of 31 percent hardwood or mixed pine hardwood and 69 percent pine. USFS fire personnel apply prescribed burns to approximately 15,000 to 18,000 acres annually to restore the native longleaf pine/savannah communities and wetland on the site (USFS 2005). A total of 28 Forest Service firefighters working at prescribed burns participated in the study during the winters of 2003 to 2005. The group included 25 men and 4 women, between 21-46 years (average: 29.8; standard deviation: 6.3), who had worked an average of 7.5 years as fire fighters at the time of recruitment. Participation in the study was voluntary. A consent form was signed after the study was explained and a firefighter had agreed to participate. The study protocol was reviewed and approved by the University of Georgia Institutional Review Board for the inclusion of human subjects.

Exposure Assessment: Personal $PM_{2.5}$ and Carbon Monoxide Sampling

Full shift personal $PM_{2.5}$ fire-fighter exposures were measured during prescribed burns (burn day) and on several days when fire-fighters did not work at burns (controls). A total of 240 samples (6.5 per day) were collected during the study, with 203 on prescribed burn days (6.7 per day). The samples were collected using SKC Air Check Model 224-PCXR pump (Eighty Four, PA) attached to BGI, GK2.05 (KTL) Respirable/Thoracic cyclone (Waltham, MA). Particulates were collected on Gelman 37 mm Teflo filter (Pall Corp., Ann Arbor, MI, USA) which was loaded into the cyclone. The filter had a 100% PTFE (poly-tetra-flouro-ethylene) Teflon membrane with a 2.0 um pore size, and a polymethylpentene support ring. The system is designed to have a 50% aerodynamic cut-off point of 2.5 μm (Kenny and Gussman, 1997). Pre and post-sampling flow rates of the pumps were measured with a Bios Dry Cal DC-Lite Model DCL20K (Bios International, Butler, NJ, USA). The flow rate for the sampling unit was set at 4.0 L/min. $PM_{2.5}$ was measured in the breathing zone with the pumps attached to each firefighter's gear-pack. In all, 149 real time person-shift CO samples were collected on 19 burn days from 20 firefighters during the 2004 and 2005 burn seasons. CO samples were not collected on non-burn days. Real-time CO was measured using Dräger Pac III single gas monitors (Draeger Safety Inc., Pittsburgh, PA) outfitted with CO sensors, and were calibrated with a 200 ppm CO certified gas standard (Calgaz, Air Liquide America Corp, Cambridge, MA) prior to the start of the study. Subsequently, Draeger CO monitors were zeroed with ambient air at the forest station at the beginning of each shift and response was checked with 200 ppm calibration gas at the end of each shift. $PM_{2.5}$ samples were collected in 2003-05, while CO was measured in 2004 and 2005.

Exposure Assessment: Questionnaire and time-activity diary

A post-shift questionnaire was administered daily to the firefighters to collect data on burn characteristics, tobacco smoke exposure, and self reported qualitative estimation of woodsmoke exposure: whether their exposure at the prescribed burns was none to very little, low, medium, medium to high, or very high. A daily activity diary administered alongside the questionnaire was used to determine the tasks and schedule of the firefighters during their work shifts. Possible job tasks included holding, lighting, mop-up, and other activities that do not belong to these major groupings. Briefly, holding involves the maintenance of fire within boundary lines, mop-up activities entail the extinguishing of smoldering fire after the major burning phase, and ignition is the fire lighting process.

$PM_{2.5}$ Gravimetric Analysis

The PTFE filters were packed and stored in a refrigerator (approximately -4C) until shipment on dry ice to the University of Georgia. The filters were stored in a climate-controlled lab for a minimum of 48 hours before they were weighed pre- and post-sample collection. Both weights were measured twice with a Cahn C-35 microbalance with a sensitivity of +/- 1 μg following the guidelines set in the USEPA's Standard Operating Procedures (USEPA 1998). The weight of the $PM_{2.5}$ collected on the filter was determined by subtracting the average pre-weight of the filter from its average post-weight. Adjustments were made for minor variations in temperature, barometric pressure and humidity for all the pre- and post-weights (USEPA, 1998). The time weighted average (TWA) particulate matter concentration was calculated as the amount of $PM_{2.5}$ collected per cubic meter (m^3) of air. Field blank concentrations were subtracted from each sample to determine the final $PM_{2.5}$ concentrations.

Statistical Analysis

All analyses were done in SAS version 9.1 (Cary, NC).

Linear mixed effect models were used to analyze the effect of various factors on $PM_{2.5}$ exposure. A plot of residuals using the un-transformed TWA $PM_{2.5}$ concentrations revealed that the constant variance assumption was not satisfied, so $PM_{2.5}$ data were log transformed before model fitting. Firefighter tasks were included in the model as dichotomous variables. Zero was assigned to a task on control days or on burn days when the firefighter had spent less than 75% of total work time on the task, and 1 on burn days when at least 75% of total work time was spent working on the task. The model included terms for plot size, wind speed and shift length (all of which were centred on their means), dichotomous variables for tasks, and the interactions between the tasks and the other variables. Interaction terms were excluded for tasks that were done on very few occasions. In addition, random subject effects were included in the model to account for longitudinal within-subject correlation among the data, and random effects for the date of sample collection were included to account for possible heterogeneity in meteorological and burn conditions from day to day.

A mixed effect model was also used to analyze how well firefighter estimation predicted actual exposure. Self-reported measures of exposure were classified as 1 to 4 depending on the subject's response in the questionnaire regarding his/her perceived level of exposure with 1 being "none to very little", 2 being low, 3 being moderate, and 4 being "high" or "very high". Exposures classified as high and very high were collapsed into one new category because of the small sample sizes in these categories.

Finally, it was desired to measure the correlation between $PM_{2.5}$ and CO and to test whether this correlation was equal to 0. This task is complicated by the presence of longitudinal correlation within this sample from repeated measures on the subjects and because of day to day heterogeneity. These features preclude a simple correlation analysis. Instead, inference on the correlation between these variables was performed by fitting a bivariate linear mixed effect model to $PM_{2.5}$ and CO simultaneously, in which random subject-specific effects and random sampling date effects for each response variable were included, and contemporaneous correlation between the two response variables was allowed and estimated.

RESULTS

In total, 240 individual $PM_{2.5}$ work shift samples were collected over the three year period: 203 of these were collected on days when prescribed burns were done. Thirty-seven non-burn activity samples were collected as controls from subjects working away from burns: 35 were collected on non burn days, two of which were from subjects carrying out high exposure fire mop-up duties. The other two control samples were collected on a burn day from firefighters who did not work at prescribed burns. In all, 28 samples were excluded from the analyses, leaving 177 burn day and 35 non-burn day samples. Seven of the burn day samples were excluded because they were collected with pumps having stop flows more than 5% below or above the calibrated volume of 4 L/min. 16 burn day samples were compromised because of problem with the cyclone, pump flow faults, or torn filters and were also excluded. Two non-burn day samples were excluded because they were collected during high exposure fire mop-up duties. In addition, three samples collected on burn days were not used in the models because data were missing for the acreage of burn the firefighters conducted.

The average duration of workshift was 10.3 hrs (range = 6.8 to 19.4 hrs) on burn days and 9.3 hrs (range = 7.0 to 11.5 hrs) on non-burn days. Samples were collected on 30 burn days with an average of 6.7 firefighters monitored per burn. The size of burn plots ranged from 1 to 2745 acres (avg = 697). Seven non-burn (control) days were monitored. The difference between average exposures on burn and non-burn days was significant. The geometric mean $PM_{2.5}$ exposure calculated from a linear mixed effect model adjusted for firefighter task, wind speed, length of work-shift, and size of burn was 280 $\mu g/m^3$ (95% CL = 140, 557 $\mu g/m^3$, n = 177) for burn day samples, and 16 $\mu g/m^3$ (95% CL = 10, 26 $\mu g/m^3$, n = 35) for non-burn day samples (Table 3.1). The unadjusted arithmetic and geometric means by year and for all samples are also presented in Table 3.1. Overall, $PM_{2.5}$ exposure ranged from 5.9 to 2673 $\mu g/m^3$, and there was no difference in exposure across the 3 years for all samples, and for either burn or non-burn day samples alone. A plot of the cumulative frequency distribution of $PM_{2.5}$ exposure is presented in Figure 3.1. TWA $PM_{2.5}$ above 1000 $\mu g/m^3$ was experienced in 11% (n = 18) of all samples included in data analysis, while exposure was above 2000 $\mu g/m^3$ and 2500 $\mu g/m^3$ in 3% (n = 5) and 1% (n = 2) of these samples respectively. There was no consistency within these samples regarding the subject or sample day. Filter $PM_{2.5}$ differed significantly across levels of the firefighters' self-assessed exposure ($p < 0.0001$ for samples collected on burn days) with a significant linear trend of increasing personal $PM_{2.5}$ exposure being observed at higher levels of self-assessed exposure ($p < 0.0001$). The adjusted geometric mean exposures for all sample days estimated as none to very little by the firefighters was 120 $\mu g/m^3$ (95% CL = 71, 203 $\mu g/m^3$), and 664 $\mu g/m^3$ (95% CL = 373, 1185 $\mu g/m^3$) for exposures estimated as high or very high on samples collected on burn days (Figure 3.2). Only the difference between exposures estimated as moderate and those estimated as high or very high was insignificant ($p = 0.06$). Exposure was not dependent on size of burn, wind speed, and length of work time.

Results of analyses suggest that type of task has an effect on exposure. However, the observed effect is solely due to tasks classified as "other" (tasks performed by the burn boss, from helicopters or not directly at the burn). The differences between pairs of job tasks excluding the "other" category were insignificant. Figure 3.3 shows geometric mean $PM_{2.5}$ exposure on burn days classified according to the job task taking up at least 75% of the firefighters' work time.

In all, 149 real time person-shift CO samples were collected during the 2004 and 2005 burn seasons. The geometric mean CO exposure (n = 149) is presented in Table I. Some pumps used for $PM_{2.5}$ sampling stopped before the end of the work-shift, so, for the purpose of the correlation analysis, the average CO samples were calculated for the periods for which the pumps ran. Also because some $PM_{2.5}$ samples were excluded from the analysis, only 134 CO/$PM_{2.5}$ pairs were used for the analysis. TWA $PM_{2.5}$ was correlated with TWA CO averaged over the run times of the $PM_{2.5}$ pumps (Pearson Correlation Coefficient estimate, $r = 0.79$; CLs: 0.72, 0.85; average duration, $t = 9.3$ hrs) (Figure 3.4), and the correlation coefficient was significantly different from zero ($p < 0.0001$). Due to the increase in variance with increasing concentrations in both variables, we decided to fit the bivariate linear mixed effect model to log-transformed values of $PM_{2.5}$ and CO simultaneously. The estimate for the Pearson Correlation Coefficient for this analysis was not substantially different and was $r = 0.73$ (CLs: 0.64, 0.82).

DISCUSSION

Studies of occupational exposures to woodsmoke among wildland firefighters in the United States have revealed that they could be exposed to levels of particulate matter exceeding the OSHA permissible exposure limit (PEL) for respirable particulates (particulates with median size 3.5 µm, $PM_{3.5}$) of 5mg/m^3 (OSHA, Code of Federal Regulation, Title 29) or the American Conference of Governmental Industrial Hygienists' (ACGIH) threshold limit value (TLV for PM_4) of 3 mg/m^3 (ACGIH 2003). These studies have mostly been done in forests in Western United States. The current study examines exposure among wildland firefighters in a forest in Southeastern United States where the vegetation and climate are very different.

It is difficult to make comparisons between this and other studies or the exposure standards because of the different size of particulate matter used in this study. Most of the previous forest firefighter exposure studies in the United States and the exposure standards are based on respirable particulates (with median aerodynamic diameter of 3.5 or 4 µm), while this study used particulate matter with median aerodynamic diameter of 2.5 microns ($PM_{2.5}$), defined by the United States Environmental Protection Agency (USEPA) as respirable particles. Various studies have shown that the aerodynamic diameter of particles in woodsmoke is mainly below 1.0 micron (Kleeman, Schauer, and Glen 1999; Leonard et al. 2007; Silva et al. 1999) and most studies of the health effects of respirable particles have used $PM_{2.5}$ as a measure of exposure.

Furthermore, we do not expect the weight concentration of $PM_{2.5}$ measured in this study would be substantially different from that of $PM_{3.5}$. McMahon and Bush (McMahon and Bush 1992) reported a 12% difference in weight concentration between $PM_{3.5}$ and $PM_{2.3}$ from small open burning greenhouse experiments using a 10 mm nylon cyclone. Subsequently, the measured exposures (geometric mean = 0.28 mg/m^3) seem to be lower than those reported by Reinhardt and Ottmar (for $PM_{3.5}$: geometric mean = 0.63 mg/m^3; n = 200) (Reinhardt and Ottmar 2004). Furthermore, higher exposures were observed among wildland firefighters during prescribed burns in an older study in Georgia, United States (for $PM_{2.3}$: median = 1.3 mg/m^3; range = 0.2-3.7 mg/m^3; n = 48) (McMahon and Bush 1992). However, exposure in the Georgia study was monitored only at the fire line and not over the entire workshift. In comparison, time spent performing tasks away from the fire during the workshift would have resulted in reduced TWA concentrations

Although the geometric mean presented here indicates that the OSHA PEL or the ACGIH TLV for particulate matter is not exceeded among this group of firefighters, exposures may exceed the TLV as a few firefighters had a $PM_{2.5}$ exposure above 2500 μg/m^3. Exposure to such elevated levels of particulate matter may elicit various adverse health effects (Dockery and Pope 1994; Dockery et al. 1993; Dominici et al. 2006). More specifically, woodsmoke exposure has been linked to respiratory symptoms and diseases (Delfino et al. 2008; Duclos, Sanderson, and Lipsett 1990; Ezzati and Kammen 2001; Naeher et al. 2007; Smith et al. 2000; Sutherland et al. 2005), and systemic inflammation (Tan et al. 2000; van Eeden et al. 2001). Lung function decline and inflammation have also been observed among wildland firefighters post-exposure to woodsmoke (Betchley et al. 1997; Swiston et al. 2008).

Daily average ambient 24-hour $PM_{2.5}$ concentrations measured by EPA monitors closest to the study site (those situated at Aiken: 1 mile NW, Edgefield: 25 miles NW, Richland: 50 miles NE, and Orangeburg: 37 miles NE Counties in South Carolina, and in Augusta, Georgia: 16 miles NW) during the periods of the study were well below most of the personal exposures of the firefighters. The maximum concentration measured by any of the monitors was less than 30 $\mu g/m^3$ throughout the periods of the study (USEPA 2008). Magnitudes of $PM_{2.5}$ exposure similar to those measured in this study have been observed for persons living in homes in which wood is used for cooking in rural communities in developing countries (Cynthia et al. 2008; Zuk et al. 2007), and in ambient air in areas impacted by wildfires in the United States (Ward et al. 2006; Wu, M Winer, and J Delfino 2006).

As observed by Reinhardt et al. (Reinhardt and Ottmar 2004), average workshift particulate matter and CO are correlated in this study confirming that either of these two environmental markers might be used as surrogate measure of exposure to the other across a prescribed burn workshift. However, the slope of the relationship in this study appears to be steeper. This could be explained by the lower carbon monoxide exposure that was observed, and possibly the difference in the aerodynamic size of the particles measured. Average exposure was not significantly affected by wind speed, wind direction, size of burn, or length of the workshift of the firefighter. Results show that firefighters tended to be able to predict their exposure. However, the variation within each estimation class is large. The observed difference in exposure across job task was solely due to tasks relatively remote from the fires. However, the comparison was not precise because firefighters often worked multiple tasks during each workshift, making the attribution of exposure during a shift to a particular task difficult. Also, very few person-hours satisfied our criterion requiring at least 75% of the workshift to be spent doing the task resulting in small sample sizes for most of the tasks in the analyses, but results did not change when the analysis was done with a relaxed classification and exposures were assigned to tasks the firefighters spent the majority of their time performing. Exposure was not completely captured in a few cases as some pumps failed to run the entire duration of the workshift. Also, exposure may be underreported in a few cases because firefighters sometimes put away their gear-packs while working at some tasks in the field. However, we do not envisage that this would have impacted our results substantially, as there was good compliance among the subjects, and the firefighters only put away their gear-packs for very short periods and only a few feet away from themselves when they do. We also kitted the subjects in this study with the samplers in order to minimize hindrance without compromising the results of the study. The use of time integrated samplers to monitor exposure across the entire workshift precluded the calculation of TWA exposure at the fire line, which would have been higher than the result presented here.

CONCLUSIONS

Although the overall geometric mean $PM_{2.5}$ exposure indicates that the OSHA PEL or the ACGIH TLV for particulate matter was not surpassed, these limits may be exceeded as some of the firefighters were exposed to very high levels of $PM_{2.5}$. The correlation between CO and $PM_{2.5}$ is potentially an exposure assessment tool for research and exposure management for firefighter working at prescribed burns.

RECOMMENDATIONS

As indicated above, the correlation between CO and $PM_{2.5}$ may be used for exposure control among wildland firefighters. CO monitors with alarms set at certain thresholds could, for example, be used to alert firefighters to a high/very high exposure situation. This could be particularly because firefighter exposure to woodsmoke may be dominated by momentary peaks (Edwards et al. 2005). However, the relationship between CO and PM may vary as indicated by the difference in the slope of the relationship in our study compared with those reported by Reinhardt and Ottmar (Reinhardt and Ottmar 2004). Therefore, future studies are needed to better understand the relationship between the two pollutants/exposure proxies. For future studies, we recommend that real time particulate matter samplers should be used, or where they are unavailable time-integrated samplers should be run for the duration when the firefighters are at the fire line. The completion of time activity diaries by researchers detailed to monitor the activities of firefighters at the fire line instead of self-administered diaries, together with the use of real time samplers would present the researcher with data to better understand the relationship between job tasks and exposure. The use of real time particulate matter samplers could also facilitate a better understanding of the relationship between particulate matter and CO. We also recommend that samplers should be worn directly on the firefighter in order to avoid underreporting in cases where firefighters put away their gear-packs. Some of these corrections have been and are being made in subsequent studies among this group of wildland firefighters.

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Table 3.1: Workshift TWA Personal Exposure to $PM_{2.5}$ and CO

		Unadjusted				Adjusted
		2003	2004	2005	Total	Total
Burn Day	$PM_{2.5}$ Arithmetic mean (CLs) ($\mu g/m^3$)	353 (242, 464)	491 (365, 617)	507 (385, 629)	462 (389, 535)	
	$PM_{2.5}$ Geomean (CLs) ($\mu g/m^3$)	215 (154, 300)	248 (184, 333)	347 (265, 456)	264 (221, 316)	280 (140, 557)
	CO Geomean (CLs) (ppm) **		1.0 (0.07, 13)	1.1 (0.14, 9.2)	1.0 (0.09, 11.6)	
	Duration of work-shift - Mean (Min, Max) (hrs)	9.0 (6.8, 10.5)	11.0 (7.8, 19.4)	10.1 (7.9, 14.5)	10.3 (6.8, 19.4)	
	Size of Burn - Mean (Min, Max) (acres)	411 (1.0, 1900)	758 (5.0, 2745)	837 (345, 1898)	697 (1.0, 2745)	
	N	43	82	52	177	
Non-burn Day	$PM_{2.5}$ Arithmetic mean (CLs) ($\mu g/m^3$)	26 (12, 39)	24 (14, 35)	12 (10, 15)	20 (15, 25)	
	$PM_{2.5}$ Geomean (CLs) ($\mu g/m^3$)	23 (13, 43)	18 (12, 27)	12 (9.0, 15)	16 (12, 20)	16 (10, 26)
	Duration of work-shift - Mean (Min, Max) (hrs)	8.6 (7.0, 9.0)	9.2 (9.0, 9.8)	9.9 (7.8, 11.5)	9.3 (7.0, 11.5)	
	N	5	17	13	35	

** CO was measured on only burn days and in 2004 and 2005 alone

** Results were adjusted for plot size, wind speed, shift length, tasks, and the interactions between the tasks and the other variables

N = 87 in 2004

N = 62 in 2005

N = 149 for all samples

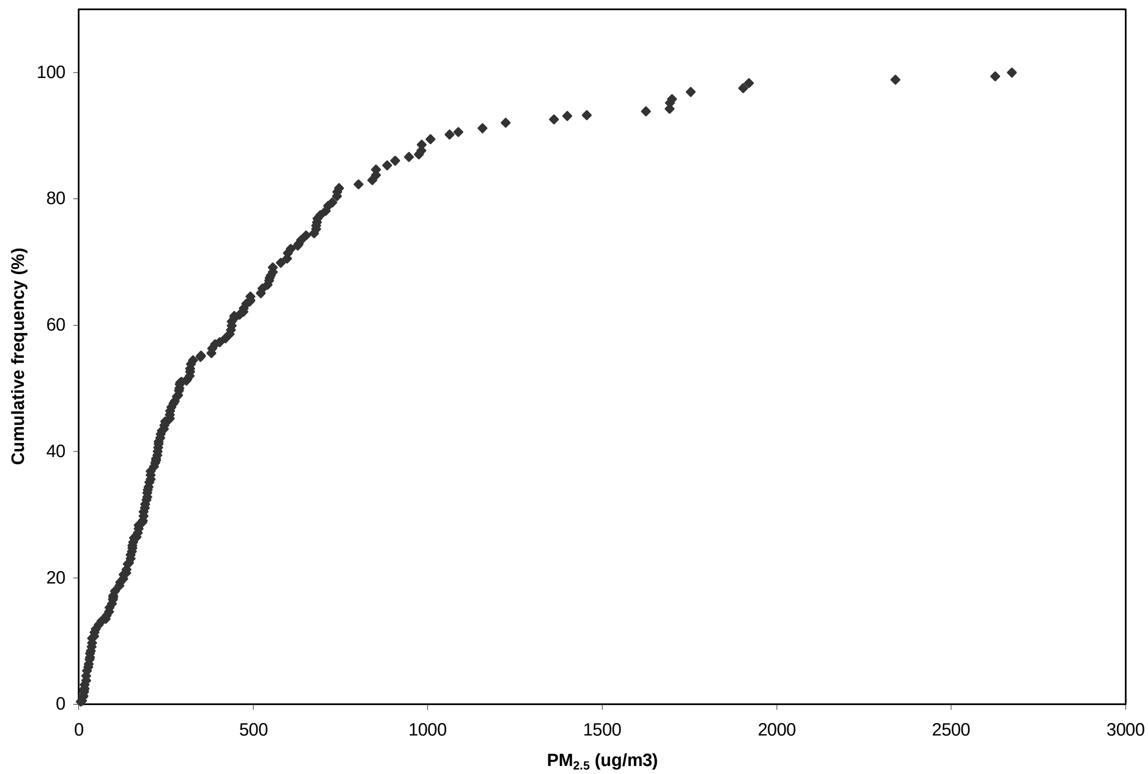

Figure 3.1: Cumulative Frequency Distribution for $PM_{2.5}$ Exposure on Burn Days
N = 177

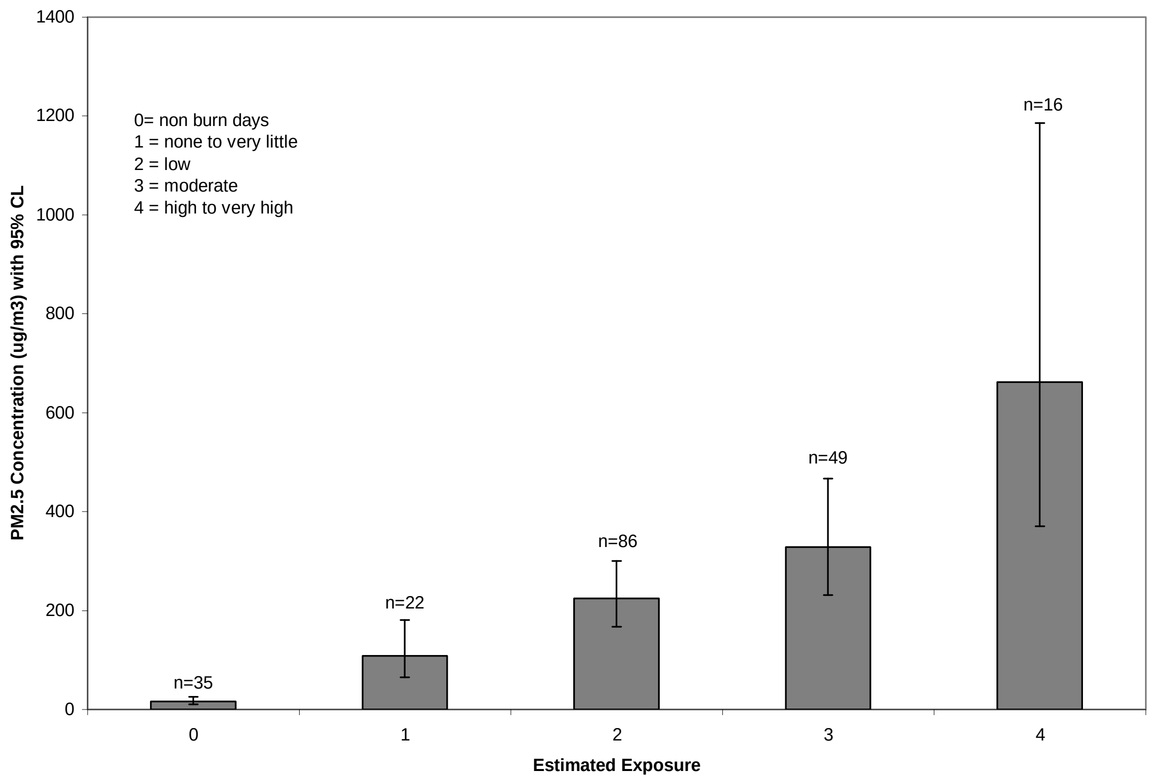

Figure 3.2: Geometric Mean Estimates of $PM_{2.5}$ at Self-Estimated Exposure Levels
N = 208 (N is fewer than 212 because some samples did not have data filled in for the self-estimation variable)
($p < 0.0001$)

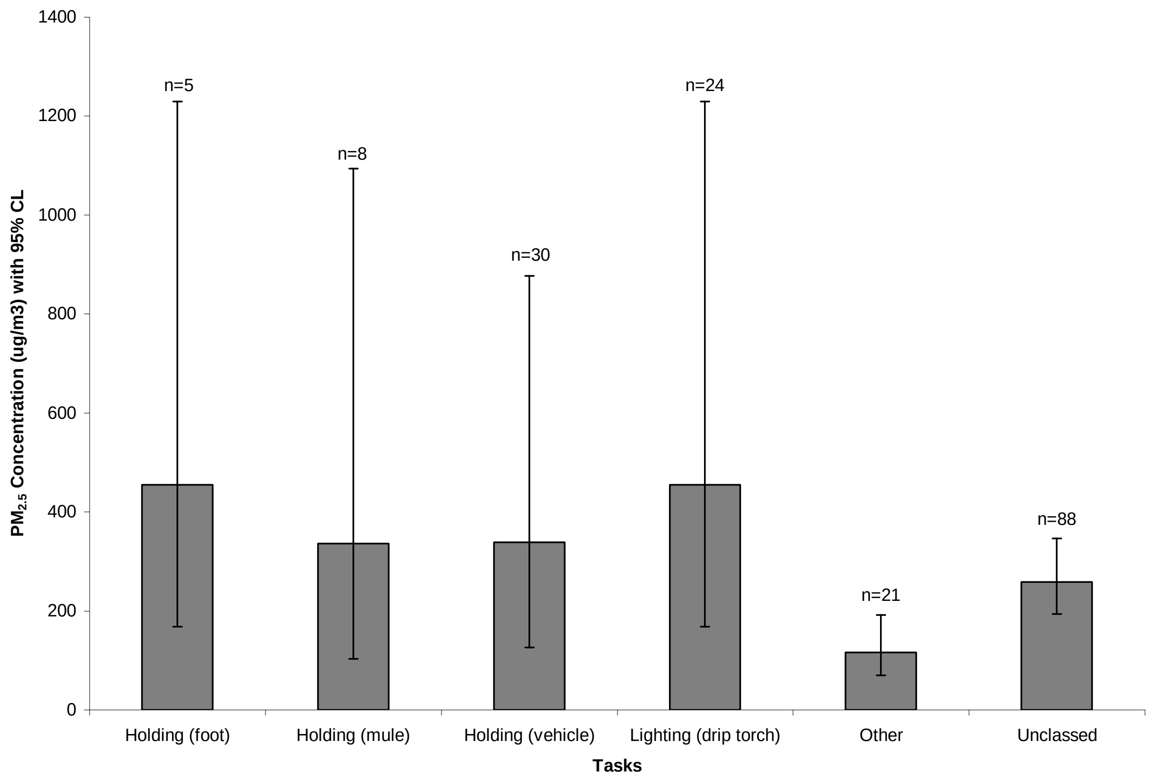

Figure 3.3: Geometric Mean Estimates of $PM_{2.5}$ Exposure on Burn Days across Different Tasks with at Least 75% of Firefighter Work Time

Holding was done on foot, on a mule (utility vehicle), or with a four-wheel car (vehicle). Lighting was done with a drip torch. Tasks not under the major classifications are categorized as "other", while the 'unclassed' category is for exposures with the proportion of workshift time spent on all tasks during the particular workshift being below 75%.

($p < 0.05$)

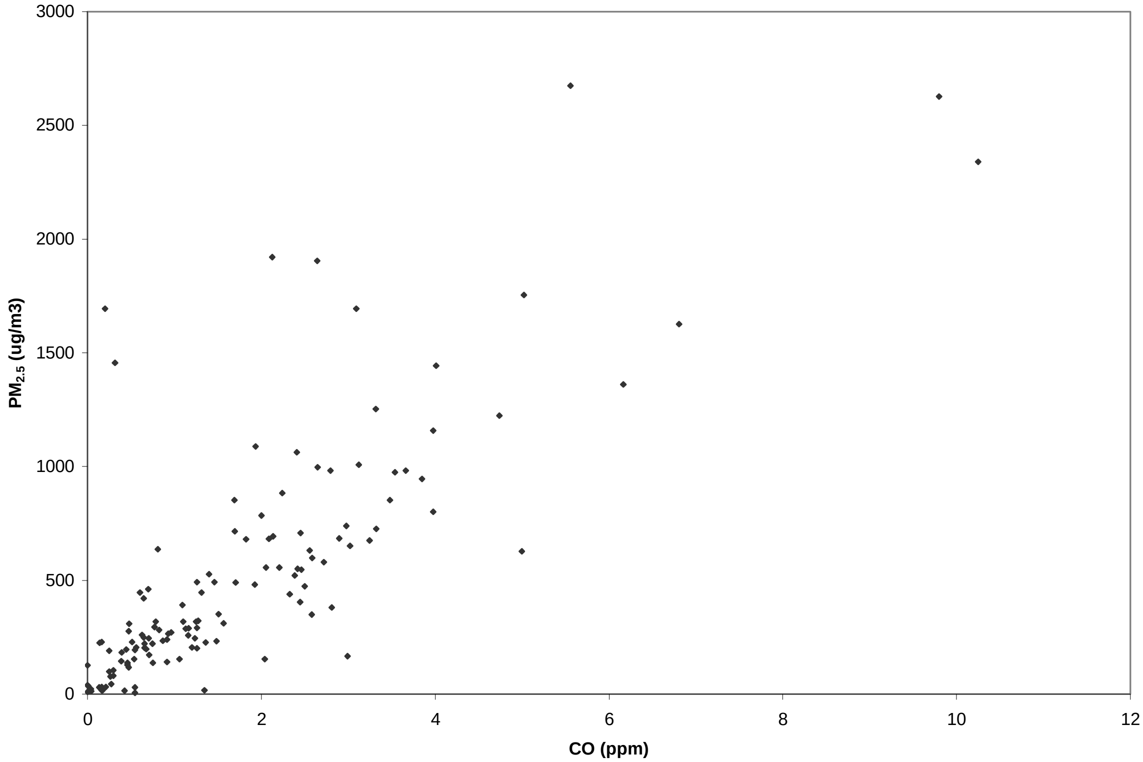

Figure 3.4: Association (Scatter Plot) between $PM_{2.5}$ and CO
Pearson Correlation Coefficient = 0.79; $p < 0.0001$ (estimated from bivariate linear mixed effect model fitted simultaneously to $PM_{2.5}$ and CO).
N = 134

CHAPTER 4

LUNG FUNCTION CHANGES IN WILDLAND FIREFIGHTERS WORKING AT PRESCRIBED BURNS[1]

[1] O. Adetona, D. B. Hall, L.P. Naeher. Submitted to Inhalation Toxicology

ABSTRACT

Context: Although decline in lung function across workshift has been observed in wildland firefighters, measurements have been restricted to days when they worked at fires. Consequently, such results could have been confounded by normal circadian variation associated with lung function.

Objectives: We investigated the across-shift changes in lung function of wildland firefighters, and the effect of cumulative exposure on lung function during the burn season.

Materials and Methods: We measured forced vital capacity (FVC), forced expiratory volume in 1 second (FEV_1), forced expiratory flow from 25% to 75% of FVC (FEF_{25-75}), and peak expiratory flow (PEF) of wildland firefighters before and after their workshifts. In all, 501 pre-shift and 488 post-shift measurements were collected over 22 burn days and 43 non-burn days from 24 non-smoking wildland firefighters during the dormant winter burn seasons of 2003 and 2004. We compared changes in the spirometry measures across the workshift on burn days to those observed on non-burn days. We also assessed the effect of cumulative exposure during the burn season on the spirometry measures.

Results: There were no significant differences in the across workshift changes on burn days compared to those on non-burn days for all the spirometry measures. However, for a given point in time during the season, each additional day of exposure was estimated to be associated with declines of 24ml in pre-shift FVC and 24ml in pre-shift FEV_1 ($p<0.01$).

Discussion and Conclusion: Cumulative exposure to woodsmoke was associated with slight decrements in lung function among the wildland firefighters.

INTRODUCTION

Wildland firefighters work to suppress wildfires, and apply prescribed burns to wildlands in order to achieve desirable land management goals. However, they could be exposed to elevated levels of woodsmoke while carrying out their duties. Woodsmoke contains many air pollutants including particulate matter, carbon monoxide (CO), aldehydes, volatile organic compounds, and polycyclic aromatic hydrocarbons (Naeher et al. 2007), and occupational exposure to respirable particles ($PM_{3.5}$) and carbon monoxide (CO) among wildland firefighters sometimes exceeds the relevant occupational exposure standards (Reinhardt and Ottmar 2000, 2004).

Woodsmoke exposure is linked with various adverse health effects, and exposure due to wildfires has been associated with acute health effects measurable by increases in hospital and emergency room visits (Duclos, Sanderson, and Lipsett 1990; Moore et al. 2006; Mott et al. 2002). Residential combustion of wood has also been linked with respiratory diseases, especially among women and children (Collings, Sithole, and Martin 1990; Orozco-Levi et al. 2006; Triche et al. 2005). Furthermore, biomarker studies show that woodsmoke exposure could induce inflammation (Tan et al. 2000; van Eeden et al. 2001). Elevations in serum levels of pro-inflammatory cytokines from pre- to post-workshift have been observed in wildland firefighters (Swiston et al. 2008).

The focus of most health studies conducted among wildland firefighters has been largely limited to lung function and respiratory symptoms, and declines in lung function across workshifts and across burn seasons have been reported (Betchley et al. 1997; Letts et al. 1991; Liu et al. 1992). Previous lung function studies of wildland firefighters were conducted mainly at wildland fires or prescribed burns in the Western United States. In the current study, we examine whether exposure to woodsmoke induces lung function changes in wildland firefighters working at prescribed burns in a forest in the Southeastern United States.

Results of studies of acute effect of occupational exposure on lung function in terms of across workshift changes could be confounded by circadian variation in lung function (Barnes 1985; Hetzel 1981; Troyanov et al. 1994). Consequently, it is important that the design of such studies allow for the separation of the effect of exposure from the changes that may have otherwise occurred during non-burn days (Gaughan et al. 2008) or the changes that occur due to the diurnal nature of lung function. However, previous studies investigating across workshift lung function changes among wildlland firefighters were not effectively designed to account for such confounding, as changes in lung function across workshifts were only measured on burn days (Betchley et al. 1997; Gaughan et al. 2008). Therefore, pre- and post-workshift spirometry measures were collected from the wildlland firefighters on burn and non-burn days in the current study; across workshift changes (from pre- to post-shift) in lung function on burn days were then compared to changes observed on non-burn days. Additionally, the effect of cumulative occupational exposure to woodsmoke on lung function was investigated since spirometry measurements were collected on multiple days during the burn season.

METHODS

Study Location

This study was conducted at the Savannah River Site (SRS), SC, which is a 198,000 acre Department of Energy industrial complex. The United States Forest Service (USFS) manages the complex's forest which is composed of 31% hardwood or mixed pine hardwood and 69% pine (USFS 2005). Twenty-four non-smoking USFS firefighters were recruited to participate in the study during the dormant winter burn seasons of 2003 and 2004. Two current smokers also elected to and were allowed to participate in the study resulting in a total of 26 subjects. Participation in the study was voluntary. Each subject had the study explained to them, and signed a consent form when they agreed to participate. The study protocol was reviewed and approved by the University of Georgia Institutional Review Board for the inclusion of human subjects.

Lung Function Measurements

Spirometry was performed using a Sensormedics OMI spirometer (Houston, TX) before and after workshifts. Each subject was coached on how to use the spirometer by the research staff before any measurement was taken. Measurements of forced vital capacity (FVC), forced expiratory volume in 1 second (FEV_1), forced expiratory flow from 25% to 75% of FVC (FEF_{25-75}), peak expiratory flow (PEF), and FEV_1/FVC were done according to the American Thoracic Society (ATS) requirements.(ATS 1995) At least, 3 acceptable and 2 reproducible forced expiratory maneuvers were required for analyses. A maximum of 8 maneuvers per session were allowed. The curve with the highest FVC+FEV_1 value was selected for analysis. Measurements were collected on multiple days both when there was a prescribed burn (burn day) and when there was none (non-burn day).

Questionnaire

A questionnaire was administered at the start of the burn seasons in 2003 and 2004 to obtain baseline information regarding the smoking status of subjects and pre-existing respiratory illnesses.

Statistical Analysis

Linear mixed effect models were used to test whether there were across (pre to post) shift changes in spirometry measures. Terms in the models included dummy variables representing whether a measurement was taken pre- or post-shift (pre-post), whether it was collected on a burn or non-burn day (fire-activity), interaction between pre-post and fire-activity, race, and gender. The pre-post by fire-activity interaction was used to assess differences in changes in lung function between burn and non-burn days. Subject and date of spirometry were controlled for as random variables due to multiple measurements on each firefighter. Linear mixed effect models were also used to analyze the effect of cumulative exposure (cumulative number of burn days) on pre-shift spirometry measures. Parameter estimates changed substantially depending on whether subjects who reported having allergies were included or excluded from analyses. Therefore, terms representing allergy status, and the interaction between cumulative exposure and allergy status were included in the models. The interaction term was used to determine whether the effect of cumulative exposure on lung function depended on the allergy status of the subject. The other terms included in the models were gender, race, and the number of days since measurements started in each season. This last variable was included in the model in order to control for probable seasonal effect due to environmental exposures. The analyses were done initially with data from non-smokers and subsequently with the inclusion of data from the two current smokers who were allowed to participate in the study. All analyses were done in SAS version 9.1 (Cary, NC).

RESULTS

The initial study subjects included 23 men (3 African American) and 1 woman, between the ages of 22 and 44 years at the time of recruitment (average=29; SD=6.7). The two current smokers who participated in the study were both women. Nine subjects reported having various allergies, while none reported having a pre-existing lung illness at baseline. Forced expiratory maneuvers selected for analyses included 501 pre- and 488 post-workshift measurements collected over 22 burn days and 43 non-burn days during the two burn seasons. A total of 462 complete pre-/post-shift pair measurements were collected; 175 complete pairs on burn days and 287 complete pairs on non-burn days.

Changes across Workshift

Declines across workshift on burn days were observed for mean individual FVC and FEV_1, but not for FEF_{25-75}, PEF and FEV_1/FVC. However, changes in both FVC and FEV_1 on burn days were not significantly different from those on non-burn days. Box plots of the changes in the spirometry measures according to burn vs. non-burn days are presented in Figure 4.1. Results were similar when current smokers were included. Results were also similar with or without the inclusion of subjects with allergies.

Effect of Cumulative Exposure

The effect of cumulative exposure on lung function during the burn season depended on the allergy status of the subject. Each additional day of working at a prescribed burn, at any given point during the burn season, was associated with declines of 24ml ($p<0.01$) in pre-shift FVC and 24ml in pre-shift FEV_1 ($p<0.01$) in non-allergic firefighters, and 8ml in FVC ($p<0.01$)

and 4ml in FEV_1 ($p<0.01$) in allergic firefighters (Table 4.1). Results did not change appreciably when data from the two smokers who participated in the study were included in the analyses. Changes in pre- and post-shift FVC through the study period for 2003 and 2004 are presented for two subjects in Figure 4.2. The figure illustrates the decline in FVC and FEV1 as the seasons progressed, the number of burns conducted by the subjects rose, and cumulative exposure to woodsmoke increased.

DISCUSSION

The current study followed a group of wildland firefighters working at prescribed burns during the dormant winter burn seasons of 2003 and 2004 in a southeastern United States forest. Although, declines across the workshift were observed for FVC and FEV_1, changes on burn and non-burn days were similar. Betchley et al. (Betchley et al. 1997), reported significant cross-shift declines from pre- to mid-shift and from pre- to post-shift in FVC, FEV_1, and FEF_{25-75} among firefighters working at forest fires in Washington and Oregon States. However, comparisons were not made against non-burn days. Swiston et al. (Swiston et al. 2008) reported no difference in changes in FEV_1 after bronchodilation at baseline and after a forest firefighting workshift. Together, these results suggest that lung function may be insensitive for assessing cross-shift effect of woodsmoke exposure among wildland firefighters. It is possible that observed cross-shift changes may not be different from changes that would otherwise have been observed during workshifts when the firefighters did not work at prescribed burns or wildfires (Gaughan et al., 2008), or that the changes were confounded by the normal circadian variation in lung function. Circadian variation in lung function has been demonstrated in healthy subjects and patients of respiratory diseases (Barnes 1985; Hetzel 1981). For instance, diurnal variations (amplitude about the daily mean) of 2.8%, 17.6%, and 1.9% in FEV_1 have been reported for two Dutch communities, among a set of hospital based subjects in the United States, and in non-asthmatics in a controlled study respectively (Borsboom et al. 1999; Medarov, Pavlov, and Rossoff 2008; Troyanov et al. 1994).

Although our study was not specifically designed for the purpose, we observed significant associations between cumulative exposure, defined as cumulative number of firefighting days during a burn season, and decrements in pre-shift FVC and FEV_1. Similar effects were observed when the post-shift measures were analyzed instead of the pre-shift values. Declines in FVC, FEV_1 and $FEF_{25\text{-}75}$ from pre- to post-season have also been reported in previous cross-seasonal studies (Betchley et al. 1997; Letts et al. 1991; Liu et al. 1992; Rothman et al. 1991). The effect of cumulative exposure on lung function during the burn season depended on the allergy status of the subject with less pronounced declines in FVC and FEV_1 being associated with each additional day of working at a prescribed burn in subjects who reported having allergies. This implies less sensitivity in lung function changes in subjects with allergies. However, this result may have been due to a small number of subjects and/or unaccounted for confounders. Furthermore, a few large burns had already been conducted (seven in 2003, four in 2004) before spirometry measurements started.

We did not collect lung function measures beyond eight days of the last burn, and did not assess whether lung function improved during the off-season. Therefore we could only explore whether the observed declines were sustained beyond the burn season by comparing spirometry measures at the start of the study periods in the two consecutive dormant winter burn seasons. There was no difference in FVC and FEV_1 between the start of measurements in 2003 and 2004 in nine subjects who participated in both years. Thus the results suggest that there was no permanent effect of woodland smoke on lung function. Betchley et al. (Betchley et al. 1997) reported that declines in FVC, FEV_1 and FEF_{25-75} during the burn season tended to resolve after a considerable number of days (average=257; SD=53.3 days) away from firefighting. However, they reported that significant decrement in FEV_1 and FEF_{25-75} compared to baseline remained 2.5 months after the last firefighting activity.

Spirometry measurements and exposure monitoring was missed for several days for some subjects. There was no exposure data for 89 person-days out of the total of 203 person-days of spirometry measurements collected on burn days. Consequently, a more accurate measure of cumulative exposure could not be determined from personal monitoring, and we used cumulative number of firefighting days to estimate this measure. Nevertheless, we observed a significant effect of cumulative exposure on lung function through one month periods with 11 days of exposure each in our study group with or without the inclusion of current smokers. We also relied on questionnaire information for the allergy status of the subjects. Furthermore, our study was specifically designed to assess across workshift changes and not the effect of cumulative exposure on within-season lung function changes. A study designed to measure declines in firefighters against those of control subjects as has been done for other groups of workers (Beeckman et al. 2001; Christiani et al. 1999; Senthilselvan et al. 1997; Ulvestad et al. 2001) would more definitively answer questions regarding within-season or longer term effects of cumulative exposure.

CONCLUSIONS

To our knowledge, this is the first study among wildland firefighters that compares changes in lung function across workshift on burn and non-burn days. Gaughan et al. (Gaughan et al., 2008) had suggested that such comparison would strengthen the inference about cross-shift changes in FEV_1 in their study of wildland firefighters at wildfires. The results in our study indicate that across shift changes in lung function on burn days were not different from those on non-burn days at the levels of woodsmoke exposure experienced by the wildland firefighters. However, a small cumulative effect was seen with multiple days of exposure. Therefore the results indicate that measurements should span a longer period of time in order to investigate the effect of occupational woodsmoke exposure on wildland firefighters. It would also be advisable to collect the pre- and post-exposure measurements during the same period of the day if the study design does not incorporate control non-exposure (non-burn days) in order to avoid confounding with diurnal effects. Alternatively, comparison of changes in lung function should be made between burn and non-burn days as was done in the current study.

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Table 4.1: Parameter Estimates from Linear Mixed Effect Models

	Estimate (ml)	
	FVC (p)	FEV_1 (p)
All subjects (n = 26)		
Gender (if subject is female)	-1840 (<0.01)	-1376 (<0.01)
Race (if subject is Caucasian)	390 (0.47)	-156 (0.78)
Worktime*	1.2 (0.35)	0.8 (<0.01)
Cumulative Burn Days**	-25 (<0.01)	-27 (<0.01)
Allergies (yes)	-176 (0.62)	-154 (0.68)
Cumulative Burn Days x Allergies (yes)	15 (<0.01)	19 (<0.01)
Subjects without smokers (n = 24)		
Gender (if subject is female)	-2877 (<0.01)	-2272 (<0.03)
Race (if subject is Caucasian)	393 (0.47)	-152 (0.80)
Worktime*	0.8 (0.56)	-0.03 (<0.03)
Cumulative Burn Days**	-24 (<0.01)	-24 (<0.01)
Allergies (yes)	-280 (0.62)	-303 (0.1)
Cumulative Burn Days x Allergies (yes)	16 (<0.01)	20 (<0.01)

* Worktime – the number of work days since study began for each burn season
** Cumulative Burn Days – number of burn days since study began for each burn season

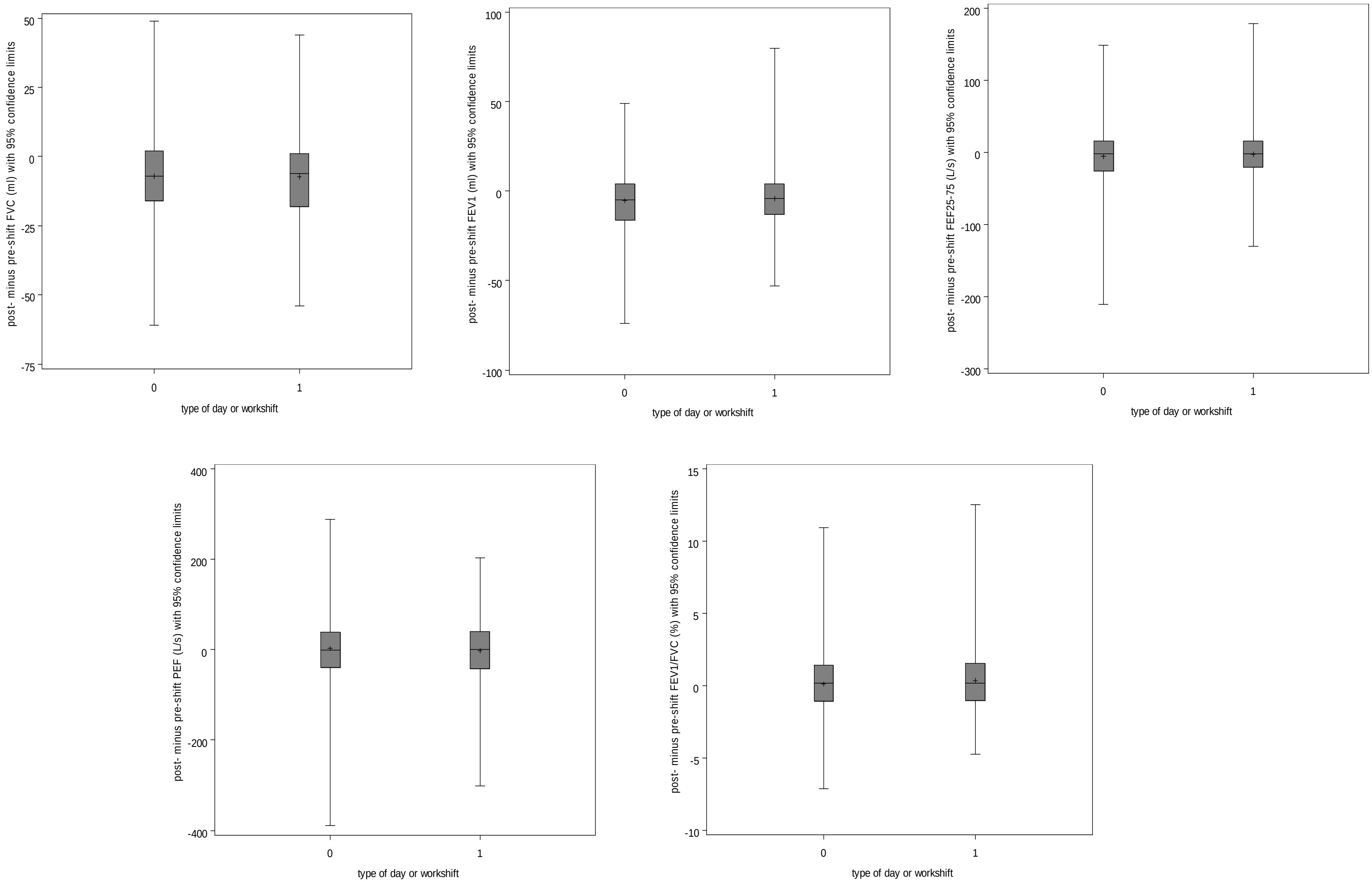

Figure 4.1: Post- minus pre-shift changes in FVC, FEV_1, FEF_{25-75}, PEF and FEV_1/FVC plotted against burn activity for non-smokers
0 = represents non-burn days (n = 287)   1 = represents burn days (n = 175)

Figure 4.2: Profile of Pre-shift FVC across 2003 and 2004 Burn Seasons for Two Subjects
* The dates that have asterix are for days when there were burns and dates without asterix are for days when there was no burn

CHAPTER 5

OCCUPATIONAL EXPOSURE TO WOODSMOKE AND OXIDATIVE STRESS IN WILDLAND FIREFIGHTERS[1]

[1] O. Adetona, J. Zhang, D.B. Hall, J-S. Wang, J.E. Vena, L.P. Naeher. Planned for submission to the Journal of Occupational and Environmental Medicine.

ABSTRACT

Introduction: Results of experimental studies indicate that exposure to woodsmoke could induce oxidative stress. However studies have not been conducted among the general population and specialized occupational groups despite the existence of elevated woodsmoke exposure situations. Therefore, we investigated whether there were across workshift changes in oxidative stress biomarkers among wildland firefighters who are occupationally exposed to elevated levels of woodsmoke.

Methods: We collected pre- and post-workshift urine samples from 19 wildland firefighters before and after prescribed burns during the dormant winter burn season of 2004. We measured malondialdehyde (MDA) and 8-hydroxy-2'-deoxyguanosine (8-OHdG) in the samples, and analyzed whether there were cross-shift changes in their levels, and the relationships between the changes and the length of firefighting career, age of firefighter, and workshift exposure to particulate matter.

Results: Overall no significant cross-shift change was observed for 8-OHdG or MDA in the urine samples of the firefighters. Changes in both biomarkers were also not associated with carbon monoxide, $PM_{2.5}$ and urinary levoglucosan which were used as markers of exposure. However, overall geometric mean 8-OHdG levels in the samples (31μg/g creatinine: unadjusted) was relatively high compared to those measured in healthy individuals in many occupational or general population studies. In addition cross-shift changes in 8-OHdG excretion could be dependent on the length of firefighting career ($p = 0.01$) or age of the subject ($p = 0.01$). Significant increases in 8OHdG level from pre-shift to post-shift were observed for those who had been firefighters for less than 2 years, while decreases were observed for those who had worked for longer periods.

Conclusions: The results indicate that oxidative stress response measured as cross-shift changes in 8-OHdG may depend on age or the length of a firefighter's career. These results suggest the need to investigate the longer term health effects of cumulative exposure of woodsmoke exposure among wildland firefighters, because increased body burden of oxidative stress is a risk factor for many diseases and even natural aging.

INTRODUCTION

Exposure to woodsmoke has been associated with various pulmonary effects including lung function decline, increases in asthma and other respiratory symptoms, upper respiratory tract illnesses, chronic bronchitis, and chronic obstructive pulmonary disease (COPD) (Kurmi et al. 2010; Naeher et al. 2007; Orozco-Levi et al. 2006; Sood et al. 2010). Fine particles are thought to be the best indicator of the health effects of exposure to emissions from most combustion sources (Naeher et al. 2007). In general, the induction of toxicity by particulate matter (PM) is believed to involve oxidative stress (Li et al. 2002; Schins et al. 2004). Woodsmoke particles contain free radicals and other substances capable of generating reactive oxygen species (ROS) within the cells. These substances include metals, polycyclic aromatic hydrocarbons (PAHs), and other organic compounds. Woodsmoke particles and woodsmoke extracts have been shown to increase the cellular generation of ROS (Leonard et al. 2007; Leonard et al. 2000; Liu et al. 2005). Other researchers have found that woodsmoke PM increased oxidative DNA damage (Danielsen et al. 2009), while woodsmoke extract induced antioxidant response systems in lung cell lines (Lee et al. 2008). Results of animal studies also indicate that woodsmoke exposure could induce oxidative stress in the whole organism.

Oxidative stress can be assessed by monitoring the changes in the excretion of urinary biomarkers, including 8-OHdG and MDA. 8-OHdG is the most studied oxidative DNA lesion and has mutagenic potential due to its ability to induce GC → TA transversions (Pilger and Rüdiger 2006). MDA is the principal product of the peroxidation of polyunsaturated fatty acid (Del Rio, Stewart, and Pellegrini 2005). Both 8-OHdG and MDA are excreted in urine and have been used as biomarkers of oxidative stress in various occupational health studies (Goulart et al. 2005; Kim et al. 2004; Liu et al. 2006; Pan et al. 2008; Wei et al. 2010).

However, except in human chamber exposure studies, the possible association of woodsmoke exposure and oxidative stress has not been investigated in typical high exposure situations despite the existence of such exposures among different population groups. A substantial number of people, especially women and children in developing countries where wood combustion still constitutes a significant amount of the residential energy supply, are chronically exposed to elevated levels of woodsmoke (Fullerton, Bruce, and Gordon 2008). In developed countries, such high exposure situations among the general population may occur during wildfire events. However, wildland firefighters who could work at tens of wildfires each year in addition to participating at prescribed burns are often the most exposed population group. Booze et al. (2004) had estimated that Type I crews who are the more highly trained wildland firefighters could work an average of 64 days at wildfires and an additional 5 days of prescribed burns per year (Booze et al. 2004). Results of previous studies among wildland firefighters show that their exposures to particulate matter in some instances exceed the American Conference of Governmental Industrial Hygienists' (ACGIH) 8-hour occupational standard of 3 mg/m^3 or Occupational Safety and Health Administration's (OSHA) 5 mg/m^3 (Materna et al. 1992; Reinhardt and Ottmar 2004).

Study of health effect among wildland firefighters has largely been limited to changes in lung function and incidences of respiratory symptoms (Betchley et al. 1997; Liu et al. 1992; Rothman et al. 1991; Serra, Mocci, and Randaccio 1996). More recently, inflammation has been examined with workshift exposure to woodsmoke being associated with increase in sputum granulocyte and serum interleukins-6 and 8; indicating that woodsmoke exposure induced both local (lung) and systemic inflammation in firefighters (Swiston et al. 2008). However, oxidative stress is yet to be studied among this group of workers.

This study investigates woodsmoke exposure induced oxidative stress in wildland firefighters as measured by cross-shift changes in urinary excretion of MDA and 8-OHdG), and the relationship of these changes with workshift exposure to particulate matter, the length of firefighting career, and the age of the firefighter. It was hypothesized that occupational exposure to woodsmoke would cause a cross-shift increase in the urinary excretion of MDA and 8-OHdG. Additionally, we analyzed for possible associations between the individual cross-shift changes in the oxidative stress markers with cross-shift changes in urinary levoglucosan. Levoglucosan is a pyrolysis product of cellulose, which along with lignin are the two main polymers in wood. It has been used as a tracer of woodsmoke particles in ambient air (Bergauff et al. 2008; Simoneit et al. 1999), and its utility as a urinary biomarker of woodsmoke exposure has been assessed in a few studies (Bergauff et al. 2009; Hinwood et al. 2008; Migliaccio et al. 2009). The full results for the assessment of urinary levoglucosan as a biomarker of occupational woodsmoke exposure in the same set of samples are presented elsewhere (Naeher and Barr 201x: in prep).

METHODS

Study Location and Subjects

The study was conducted among the United States Forest Service (USFS) wildland firefighter crew at the Savannah River Site (SRS), located in the southeastern coastal area of the United States. The 198,000 acre site is a National Environmental Research Park. The USFS firefighter crew treats 15,000 to 18,000 acres of the park's forest, which comprises of 31 percent hardwood or mixed pine hardwood and 69 percent pine, annually with prescribed burns. Participation in the study was voluntary and a total of 19 firefighters (17 men and 2 women) volunteered and gave pre- and post-workshift urine samples during the dormant winter (January to March) prescribed burn season in 2004. The age of subjects at the time of the study ranged between 21 and 44 years (average: 29.8; standard deviation: 6.1). Subjects were enlisted after the study was explained to them and they had signed a consent form. The study was approved by Institutional Review Boards of the University of Georgia, Athens, GA and the Centers for Disease Control and Prevention (CDC). The study was part of a larger occupational woodsmoke exposure study conducted during the winter burn seasons of 2003-2005 (Adetona et al. Accepted for publication, scheduled to be published August 2011).

Urine Sample Collection

Pre-workshift spot urine samples were provided by the subjects between 6:00 am and 9:00 am in the morning at the fire office before they proceeded to the site of the day's burn(s). Post-workshift samples were provided by the subjects on return to the fire office after the day's burn. Samples were collected in 50 ml polypropylene centrifuge tubes, put on dry ice and shipped to the National Center for Environmental Health laboratory at the Centers for Disease Control and Prevention (CDC) in Atlanta, GA, USA for storage where they were frozen at -80 °C. The samples were later shipped to the School of Public Health, University of Medicine and Dentistry of New Jersey, NJ for 8-OHdG and MDA analyses.

Exposure Assessment – CO, $PM_{2.5}$ and Urinary Levoglucosan

The methods for monitoring/assessing exposure have been reported elsewhere (Adetona et al. Accepted for publication, scheduled to be published August 2011). Briefly, personal exposures of the subjects to CO and $PM_{2.5}$ were monitored for the duration of the workshift with samplers placed in the subject's breathing zone. CO was monitored in real time with the Drager

Pac III single gas monitors (Draeger Safety Inc., Pittsburgh, PA) outfitted with CO sensors. Time integrated exposure to $PM_{2.5}$ was monitored using SKC Air Check Model 224-PCXR pump (SKC Inc., Eighty Four, PA, USA). Particles were collected on Gelman 37 mm Teflo filter (Pall Corp., Ann Arbor, MI, USA) which were loaded into a BGI GK2.05 (KTL) Respirable/Thoracic cyclone (Waltham, MA, USA). The concentration of $PM_{2.5}$ was determined gravimetrically.

Post-shift questionnaires were administered daily to the firefighters to collect information regarding possible confounding exposures such as first and second hand (cigarette/tobacco) smoke exposure at work and at home. Questionnaires were also administered at the start of the study to collect information relating to subjects' baseline health and smoking status.

The analytical method for levoglucosan has been reported elsewhere (Naeher and Barr 201x: in prep). Levoglucosan in the urine samples was analyzed using gas chromatography-tandem mass spectrometry (GC/MS-MS). Briefly, aliquots of the samples were extracted using acetonitrile, and then derivatized using a mixture (ratio 1:4) of N-trimethylsilylimidazole (TMSI) and pyridine. The derivatized extract was then loaded onto a ChemElut liquid/liquid extraction cartridge. The target analyte was eluted with hexane, evaporated to dryness, then reconstituted in toluene and transferred to GC autosampler vials. The sample was then automatically loaded into the GC, and was analyzed by mass spectrometer.

8-hydroxy-2'-deoxyguanosine Analysis

8-OHdG concentration in thawed (at room temperature) urine samples was determined using the HPLC/ECD method. The thawed urine samples were first centrifuged at 3200 rpm for 15 minutes. A solution of 1.5 ml aliquot of the sample and 1.5 ml potassium dihydrogen phosphate buffer (KH_2PO_4) (0.1 M, pH 6) was then applied to a solid phase extraction cartridge

(Certify, Varian) already conditioned with 5 ml methanol, 5 ml deionized (DI) water and 5 ml KH_2PO_4 (0.1 M, pH 6). The cartridge was then washed with 3 ml DI water and 1.5 ml KH_2PO_4 (0.1 M, pH 6) and vacuum dried for 30 minutes at -20 inHg. 8-OHdG was eluted from the cartridge by 2 ml solution of 30% methanol in DI water, and 20 µl of the eluted solution was injected into the HPLC/ECD system (Alliance Waters 2695 with 2465 Electron-Chemical Detector). 8-OHdG was detected by a Waters ECD at a potential of +0.6 V, a range of 50 nA and a time constant of 1.0 s. The separation of 8-OHdG was carried out on a RP-C18 (250 mm x 4.6mm, 5um, Waters, US) HPLC column with the temperature of the column set at room temperature. The mobile phase for the elution of 8-OHdG from the column was composed of Solution A(Citric acid: 2.4g, Sodium acetate: 2.1g, Acetic acid: 0.6ml, Sodium hydrate: 1.2g, EDTA: 20mg in 1 L volumetric flask with 65 ml methanol) and Solution B (Citric acid: 2.4g, Sodium acetate: 2.1g, Acetic acid: 0.6ml, Sodium hydrate: 1.2g, EDTA: 20mg in 1 L volumetric flask with 100 ml methanol). A linear calibration curve that ranged from 6.25 to 400 ng/ml was obtained using aqueous solutions of 8-OHdG standard (Sigma-Aldrich, US). The recovery rate of the analytical procedure was 99.2% with an analytic precision of 4.41% (coefficient of variation of n = 5 replicates), and a detection limit of 1.93 ng/ml.

Malondialdehyde Analysis

MDA in thawed (at room temperature) urine samples was determined using the HPLC/FD method. Firstly, 100 µl of the sample was centrifuged at 3200 rpm for 15 minutes. Thereafter, 50 µl of the supernatant and standard were derivatized by the addition of a solution of 500 µl 440mM phosphoric acid and 250 µl 42Mm thiobarbituric acid (TBA, Fluka Co., US) solution in sample tubes. These were then heated in the oven at 80°C for 1 hour. A solution of

1M sodium hydroxide (NaOH) was then added to neutralize the acid. Thereafter, 20 µl of the prepared solution was injected into the HPLC/FD system (Alliance Waters 2695 with 2475 Fluorescence Detector). Wavelength for excitation for the detection of MDA was set at 532 nm and emission at 553 nm. The separation of MDA was carried out on a Nova-Pak C18 (150 mm x 3.9 mm, 4 um, Waters, US) column with the temperature of the column set at room temperature. The mobile phase for the elution of 8-OHdG from the column was composed of Potassium dihydrogenphosphate: 6.8 g in 1 L methanol and water mixed solution (methanol:water=4:6). A linear calibration curve that ranged from 2 to 400 nM was obtained using TBA-MDA derivative solutions as the MDA standard (1,1,3,3-tetraethoxypropane, TEP, Sigma-Aldrich, US). The recovery rate of the analytical procedure was 75.9% with an analytic precision of 3.44% (coefficient of variation of $n = 5$ replicates), and a detection limit of 1.76 nM.

Statistical Analysis

Inference on the correlation between urinary 8-OHdG and MDA, and between each of these oxidative stress biomarkers and urinary levoglucosan was performed by fitting a multivariate linear mixed effect model to 8-OHdG, MDA and levoglucosan simultaneously, in which random subject-specific effects and random sampling date effects for each response variable were included, and contemporaneous correlation between the three response variables was allowed and estimated.

Data were analyzed with linear mixed effect models to test whether there were across workshift changes in 8-OHdG and MDA, and whether these changes were associated with workshift exposure to particulate matter, length of firefighting career and age of the firefighter. The response variables were the individual cross-shift changes calculated as the differences between the log transformed concentrations of creatinine adjusted pre-shift and post-shift 8-OHdG and MDA. The predictor variables included workshift exposure to $PM_{2.5}$, the number of firefighting years and age of the subject. These were first included separately and then together in the models. The length of firefighting career and age of the firefighter were correlated with each other. $PM_{2.5}$ was chosen as the proxy of exposure to be included in the models because it is considered the best single indicator of the health effect of combustion sources (Naeher et al. 2007). The number of firefighting years was a 4-level categorical variable with boundaries set using the quartiles of the distribution of the continuous variable. A centered variable representing day since sample collection started was also included in the models. Random subject effects were included in the models to account for longitudinal within-subject correlation among the data, and random effects for the date of sample collection were included to account for possible heterogeneity in baseline oxidative stress status of individual subjects from day to day.

All statistical analyses were performed using SAS version 9.1 (Cary, NC).

RESULTS

The overall geometric mean exposure to $PM_{2.5}$ and CO which were originally reported by Adetona et al (Adetona et al. Accepted for publication, scheduled to be published August 2011). and the unadjusted geometric mean concentrations for 8-OHdG and MDA categorized by the number of years the subjects had spent working as firefighters are presented in Table 5.1.

In all, 214 spot urine samples were collected from the subjects across 10 burn days during the period samples were collected for the current analyses; between 7 and 14 subjects participated each day of the study. One out of the 19 subjects provided just one spot sample, and so was excluded from the analyses used to test whether there were significant cross-shift changes in creatinine adjusted 8-OHdG and MDA, and whether these were associated with exposure markers. Another subject, one of the two female subjects, was excluded from the analyses due to being the only current smoker in the study. In the end, 94 person-day complete pre- and post-shift pairs of urine samples from 17 subjects were used in these analyses.

Cross-shift changes in creatinine adjusted 8-OHdG and MDA were not correlated. They were also not correlated with cross-shift changes in creatinine adjusted levoglucosan. None of the biomarkers were correlated in the pre-shift samples, and only creatinine adjusted 8-OHdG and levoglucosan in the post-shift samples were weakly correlated ($\rho_{est} = 0.24$; $p = 0.04$). It was not possible to estimate the correlation between the oxidative stress biomarkers, and urinary methoxyphenol concentrations measured in a subset of the samples using the models earlier described due to small sample size. Methoxyphenols were analyzed in only 20 pairs of pre- and post-shift samples (Neitzel et al. 2008). However, a simple correlation analysis and scatter plot suggest that 8-OHdG and MDA were not associated with urinary methoxyphenols irrespective of whether pre- or post-shift levels or the difference between both measures was the variable that was used.

The parameter estimates for the predictor variables in the models (models with the length of firefighting career, age or workshift exposure to $PM_{2.5}$ alone, and models with all the possible combinations of the variables) are presented in Table 5.2. Neither age nor the length of firefighting career was significant as a factor when included in the models individually, or together with the other predictor variable(s) for cross-shift change in MDA ($p > 0.05$). $PM_{2.5}$ was not associated with cross-shift changes in either 8-OHdG or MDA when included in the models individually, or together with the other predictor variable(s) ($p > 0.05$).

Both age and the length of firefighting career were significant factors for cross-shift change in 8-OHdG when included individually in the models. Neither of them was significant when both variables were included together and/or with workshift exposure to $PM_{2.5}$ in the models. There was a significant increase ($p = 0.04$) of 0.79 log units of creatinine adjusted 8-OHdG from pre- to post-shift among the 3 subjects who had worked as wildland firefighters for 2 years or less when only the length of firefighting years was included as a covariate together with day since sampling collection started in the model. These subjects had provided a total of 21 complete pairs of samples. In contrast, there was a change of -0.90 ($p = 0.03$) for the 4 subjects who had worked as firefighters for 10 years or more. Changes for subjects who had worked 3-5 years ($n = 5$) or 5-10 years ($n = 5$) were also negative but insignificant at $p = 0.05$ (Figure 5.1). These results were consistent with the significant negative trend associated with age in cross-shift change in 8-OHdG (Table 5.2) when only age was included as a covariate together with day since sampling collection started in the model. The models with the length of firefighting career as a predictor variable had better fit as evaluated with the Akaike Inclusion Criteria (AIC) compared with corresponding models with age as a predictor variable. The models with the length of firefighting career had lower AIC values.

DISCUSSION

Despite the exposure of a substantial number of people globally to elevated levels of woodsmoke and the concern that woodsmoke may induce toxicity via an oxidative stress mechanism, the possible association of woodsmoke exposure and oxidative stress has not been studied in humans outside of exposure chamber experiments (Barregard et al. 2008; Barregard et al. 2006; Danielsen et al. 2008). Although human experimental studies have the advantage of reducing confounding, exposures must be limited and are not similar to exposure patterns – in length and frequency – of exposed population groups including women and children exposed indoors in developing countries, and wildland firefighters while working at wildfires or prescribed burns. In this study, we assessed the possible effect of occupational woodsmoke exposure on oxidative stress among wildland firefighters who experience exposures to particulate matter well above the recommended concentrations for ambient air (Reinhardt and Ottmar 2004).

We did not observe increased lipid peroxidation as measured by cross-shift changes in creatinine adjusted MDA. Similarly, none of the predictor variables (age, length of career and workshift exposure to $PM_{2.5}$) was associated with cross-shift change in creatinine adjusted MDA. However, results from a human chamber exposure study indicate that woodsmoke exposure could induce measurable increase in lipid peroxidation in humans (Barregard et al. 2008). MDA levels were increased in exhaled breath condensate of subjects in the experiment indicating exposure to woodsmoke at least induced lipid peroxidation in the respiratory tract.

Although the direction in cross-shift changes of creatinine adjusted 8-OHdG was not consistent, the overall average concentrations in spot samples in this study (Table 5.1) are relatively higher than those measured in healthy individuals in many occupational or general population studies. These previous studies measured average 8-OHdG concentrations typically below 20 µg/g creatinine (Chuang et al. 2003; Han, Donovan, and Sung 2010; Harri et al. 2005; Kim et al. 2004; Kimura et al. 2006; Lai et al. 2005; Lee et al. 2010; Pilger and Rüdiger 2006) as against the overall unadjusted mean of 31 µg/g creatinine in this study. This suggests sustained increase in oxidative stress during the burn season when exposure to elevated levels of woodsmoke is very frequent. The firefighter crew from which the subjects in this study were drawn had conducted 10 prescribed burns within the space of 16 days when urine samples were collected. Geometric mean personal $PM_{2.5}$ exposure during the workshifts (mean length: 11.0 hrs) on the prescribed burn days as measured gravimetrically using time integrated samplers was 248 $\mu g/m^3$ (CLs: 184, 333 $\mu g/m^3$) (Adetona et al. Accepted for publication, scheduled to be published August 2011).

Oxidative stress has been identified as a potential mechanism for the induction of toxicity by PM pollution (Li et al. 2002). Woodsmoke PM is capable of generating ROS within the cell (Leonard et al. 2000), and inducing increased oxidative DNA damage. A three-hour exposure to woodsmoke PM increased strand breaks (SB) and formamidopyrimidine-DNA-glycosylase (FPG) sites in both human A549 lung epithelial and THP-1 monocytic cell lines (Danielsen et al. 2009). Woodsmoke PM was also found to generate higher levels of DNA damage per unit mass in these cells compared to traffic generated PM. Results in other in-vitro studies also indicate that woodsmoke PM may upregulate antioxidant response systems (Lee et al. 2008; Liu et al. 2005).

Furthermore, the expression of oxoguanine glycosylase (hOGG1) in peripheral blood mononuclear cells increased significantly 20 hours after exposure to woodsmoke compared to 20 hours after exposure to filtered indoor air; although no significant increases in SB and FPG sites were observed three and 20 hours after a four hour exposure period to woodsmoke in a human experimental study (Danielsen et al. 2008). (The oxidatively induced lesion, 8-oxo-7,8-dihydroguanine (8-oxoG) is removed from the DNA by hOGG1). An enhanced DNA repair capacity was adduced as a possible reason for the lack of increased levels of DNA damage. Also, there were non-significant increases in the urinary excretion of 8-oxoG and 8-oxodG 20 hours after exposure to woodsmoke.

We observed that cross-shift changes in the urinary excretion of 8-OHdG could be affected by the number of years the subjects had spent working as wildland firefighters (firefighting years). Cross-shift increase in creatinine adjusted 8-OHdG was only observed in subjects who had worked for two years or less as wildland firefighters. However, this result was confounded by age, which was correlated with firefighting years. Occupational exposures, including, to particulate matter or its components have been associated with increased urinary excretion of 8-OHdG (Han et al. 2010; Kim et al. 2004; Lee et al. 2010; Liu et al. 2006; Nuernberg et al. 2008; Wei et al. 2010). An increase in creatinine adjusted 8-OHdG across the workshift was observed among boilermakers exposed to residual oil fly ash (Kim et al. 2004). Increased urinary 8-OHdG has also been observed in coke oven workers (Liu et al. 2006), and different types of workers exposed to vehicular/traffic emissions (Han et al. 2010; Lai et al. 2005; Lee et al. 2010; Wei et al. 2010). Exposure to particulate PAHs, which are also present in relatively substantial amounts in woodsmoke PM (Kocbach et al. 2006), were associated with post workshift levels of 8-OHdG in urine in security guards exposed to particulate matter dominated by vehicular emissions (Wei et al. 2010).

The lack of absence of a cross-shift increase in, and the relatively elevated levels of 8-OHdG in subjects who had worked as wildland firefighters for longer than two years could partly have been because of adaptation due to the up-regulation of antioxidant enzymes. Exposure to exogenous factors that could induce the generation of ROS such as smoking, environmental exposure to tobacco smoke, cooking oil fumes, and exercise have been associated with increased activity of antioxidant enzymes (Asami et al. 1996; Cherng et al. 2002; Howard et al. 1998; McCusker and Hoidal 1990; Radak, Chung, and Goto 2008). Although, the generation of ROS increases during exercise, regular exercise is associated with decrease in the incidence of oxidative stress related diseases (Radak et al. 2008). Regular exercise on the treadmill has been shown to reduce 8-oxodG in the DNA, and to increase the activity of hOGG1 in cells in liver tissue of rats (Nakamoto et al. 2007). DNA repair activity as measured by the endonuclease nicking assay was significantly increased in blood leukocytes of smokers compared to non-smokers, and was correlated with the number of cigarettes smoked per day (Asami et al. 1996). Other antioxidant enzymes, in addition to DNA repair enzymes, that may be up-regulated in smokers relative to non-smokers include catalase and superoxide dismutase (McCusker and Hoidal 1990) which remove hydrogen peroxide and superoxide anion from the cell, and therefore mitigate against oxidation of macromolecules by these oxidants or their reactive products (Jarrett and Boulton 2005).

We measured actual exposures by monitoring personal exposures to $PM_{2.5}$ during the workshift. However, we did not observe a significant relationship between workshift $PM_{2.5}$ exposure and 8-OHdG or MDA. $PM_{2.5}$ has been identified as the chief indicator of the health effect of exposure to pollution from combustion sources (Naeher et al. 2007); and ambient air exposures to $PM_{2.5}$ has been observed by other researchers to be significantly associated with urinary 8-OHdG and MDA among the elderly and young children (Bae et al. 2010; Kim et al. 2009; Ren et al. 2010). There was also significant association between personal exposure to $PM_{2.5}$ and urinary 8-OHdG among boilermakers (Kim et al. 2004). There was no correlation between cross-shift changes in urinary levoglucosan and 8-OHdG or MDA. Although levoglucosan is a pyrolysis product of wood, and is abundant in woodsmoke (Bergauff et al. 2008), its proportion in PM (and thus concentration in woodsmoke) varies over a wide range, while diet could also serve as a source of exposure for levoglucosan (Bergauff et al. 2009). We also did not observe a consistent increase in urinary levoglucosan across the workshift in the urine samples that were used in this study (Naeher and Barr 201x: in prep).

We had a convenience sample, and subjects were not randomly selected for recruitment into the study. The sample size of the study was also small, and perhaps limited the chance of detecting whether cross-shift changes was dependent on the number of years the subjects had spent working as wildland firefighters, especially in the models that included additional predictor variables. Finally, the firefighter crew had conducted four prescribed burns prior to the first day of the study and sometime worked consecutive days raising the possibility of a carry over effect. However, there was an eight-day gap between the first burn in this study and the immediately preceding burn. Furthermore, results were similar when data were analyzed for the subset of the data representing samples collected on the four days when the firefighters had at least a one day break away from firefighting.

CONCLUSION

In this study, we observed relatively high levels compared to data in the literature for the excretion of 8-OHdG in wildland firefighters, suggesting they experienced sustained increase in oxidative DNA damage during the burn season. We also observed that cross-shift changes in the excretion of 8-OHdG could depend on the length of the firefighting career, with more observable increases for firefighters who had spent the least number of years at the job. However, this result was confounded by age, and the power to detect cross-shift changes was probably limited by the smallness of the sample size. Nevertheless, results from a study of a Type I hotshot crew (specially trained wildland firefighters often deployed to fight large and complex fires) showed that the score (severity) of upper respiratory symptoms among the firefighters was associated with the cumulative time spent fighting wildfires over the subjects' careers (Gaughan et al. 2008). We therefore recommend that larger studies of the long term effect of occupational woodsmoke exposure, and possible differential health responses based on the length of firefighting career be conducted.

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Table 5.1: Unadjusted geometric mean concentrations of exposure markers and oxidative stress biomarkers by the length of firefighting career

Exposure Environmental and Biological Markers

Marker (unit) (total no of samples)	Geometric Mean (CLs)
$PM_{2.5}$ ($\mu g/m^3$) (82)	248 (184, 333)
CO (ppm) (78)	1.0 (0.07, 13)

Oxidative Stress Biomarkers

	Geometric Mean (Confidence Limits)	
Firefighting Years (no of subjects, total no of samples)	8-OHdG (µg/g creatinine)	MDA (µmol/g creatinine)
0 - 2 (3, 43)	11 (2.5, 50)	0.69 (0.41, 1.15)
3 - 5 (5, 57)	50 (8.0, 308)	0.72 (0.46, 1.41)
6 - 9 (5, 69)	47 (14, 155)	0.78 (0.42, 1.46)
>/= 10 (4, 31)	22 (4.5, 104)	0.63 (0.42, 0.94)
All (17, 200)	31 (6.1, 157)	0.72 (0.42, 1.22)

* The averages were calculated excluding data from the one current smoker in the study

Table 5.2: Parameter estimates and p-values for variables in linear mixed effect models used to test for across shift differences (log (post) – log (pre)) in creatinine corrected MDA and 8-OHdG. Three models were fitted with at least one covariate alongside the day since the study began: age alone, number of firefighting years alone, and both variables together.

	MDA			8-OHdG		
	Estimate	p	AIC	Estimate	p	AIC[a]
			*Adjusted for age alone***			
Studydays	-0.012	0.29	173.6	-0.046	0.16	380.8
Age	-0.013	0.44		-0.108	0.01	
			*Adjusted for firefighting years alone***			
Studydays	-0.012	0.23	167.8	-0.046	0.16	371.8
Firefighting years (overall)		0.61			0.03	
Firefighting years (0-2 years)	-0.133	0.63		1.78	0.004	
Firefighting years (3-5 years)	-0.306	0.23		0.943	0.10	
Firefighting years (6-9 years)	-0.262	0.3		0.777	0.16	
			*Adjusted for $PM_{2.5}$ exposure alone***			
Studydays	-0.005	0.69	134.5	-0.056	0.19	300.7
$PM_{2.5}$ exposure	-0.082	0.12		0.097	0.59	
			Adjusted for firefighting years and age			
Studydays	-0.012	0.22	170.9	-0.046	0.15	374.2
Age	-0.037	0.12		-0.068	0.19	
Firefighting years (overall)		0.3			0.38	
Firefighting years (0-2 years)	-0.491	0.17		1.169	0.12	
Firefighting years (3-5 years)	-0.583	0.07		0.44	0.52	

Firefighting years (6-9 years)	-0.392	0.14		0.558	0.33	
*Adjusted for age and $PM_{2.5}$ exposure***						
Studydays	-0.004	0.77	139.2	-0.042	0.31	296.2
Age	-0.023	0.26		-0.131	0.008	
$PM_{2.5}$ exposure	-0.085	0.1		0.064	0.71	
*Adjusted for firefighting years and $PM_{2.5}$ exposure**						
Studydays	-0.006	0.64	135.6	-0.048	0.25	289.1
$PM_{2.5}$ exposure	-0.093	0.08		0.141	0.42	
Firefighting years (overall)		0.7		0.05		
Firefighting years (0-2 years)	-0.033	0.92		1.916	0.008	
Firefighting years (3-5 years)	-0.295	0.38		1.752	0.02	
Firefighting years (6-9 years)	-0.257	0.42		1.316	0.05	
Adjusted for all variables						
Studydays	-0.003	0.75	137.9	-0.04	0.35	291.0
Age	-0.047	0.1		-0.088	0.19	
$PM_{2.5}$ exposure	-0.099	0.06		0.114	0.52	
Firefighting years (overall)		0.4			0.49	
Firefighting years (0-2 years)	-0.504	0.25		1.159	0.21	
Firefighting years (3-5 years)	-0.655	0.1		1.098	0.23	
Firefighting years (6-9 years)	-0.535	0.19		1.054	0.13	

a: AIC means Akaike Information Criterion (used to check the fit of the model)
* Models in which length of firefighting career is marginally significant as a predictor of cross-shift change in 8-OHdG
** Models in which length of firefighting career or age is a significant predictor of cross-shift change in 8-OHdG

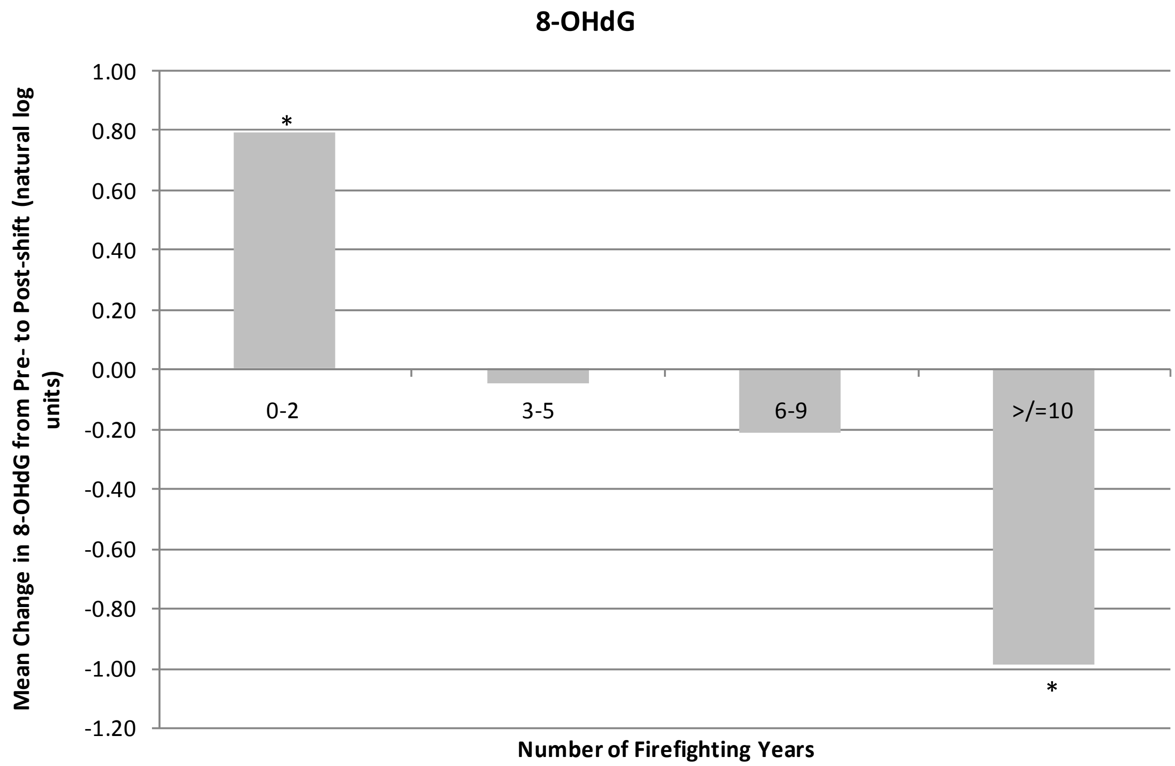

Figure 5.1: Mean change from pre- to post-shift in log units of creatinine corrected 8-OHdG according to the number of fighting years. Results presented here are unadjusted for age
* Significant at p = 0.05

CHAPTER 6

CHARACTERIZATION OF WILDLAND FIREFIGHTER EXPOSURE TO CARBON MONOXIDE AND $PM_{2.5}$ USING REAL TIME AEROSOL MONITORS[1]

[1] O. Adetona, D.B. Hall, L.P. Naeher. Journal to be decided

ABSTRACT

Introduction: Previous exposure studies have mostly characterized $PM_{2.5}$ exposure among wildland firefighters using time integrated exposures averaged over the duration of the firefighter workshift or work at the fireline. Exposure to $PM_{2.5}$ in this study is characterized in real time and the data are used to explore whether $PM_{2.5}$ and CO are correlated in real time, investigate the contributions of peak exposures to the overall exposure, and determine the effect of job task on exposure.

METHODS: 60 individual person-day real time CO and 37 $PM_{2.5}$ samples were collected from 15 firefighters over 10 burn days at the fireline while they worked at prescribed burns. Time activity diaries were used to collect information regarding the job tasks of the firefighters. Questionnaires were administered post-shift to identify possible confounding exposures that the firefighters may have experienced while working at the burns.

Results: Peak exposures contributed substantially to the overall exposures of the firefighters. The percentage of time at the fireline with exposure above 3 mg/m^3 ranged between 2.6% and 40%, and accounted for 24% to 82% of the exposure. Plots of concurrently measured real time CO and $PM_{2.5}$ indicated that exposure to both pollutants correlated well over shorter temporal resolutions. Exposures to both CO and $PM_{2.5}$ differed by task ($p<0.01$). Persons who were “holding” had the highest exposures to both pollutants, and had the most exposure incidences exceeding the recommended excursion short term exposure limits.

Conclusions: We characterized exposure to $PM_{2.5}$ in real time and obtained results that could be useful for managing wildland firefighter exposure to woodsmoke. Peak exposures over a relatively small amount of time contributed substantially to overall exposures. Variation of

concurrently measured CO and $PM_{2.5}$ closely mirrored each other across periods of very small temporal resolution.

INTRODUCTION

Previous occupational studies of woodsmoke exposure among wildland firefighters show that they are exposed to elevated levels of particulate matter (PM), and suggest their exposures should be controlled or managed (Materna et al. 1992; McMahon and Bush 1992; Reinhardt and Ottmar 2000, 2004; Reinhardt, Ottmar, and Hanneman 2000). While wildland firefighters' workshift and fireline time weighted average (TWA) exposures are often below the Occupational Safety and Health Administration's (OSHA) 8-hour occupational permissible exposure limit (PEL) of 5 mg/m^3, and even the American Conference of Governmental Industrial Hygienists' (ACGIH) recommended threshold limit value (TLV) of 3 mg/m^3, their exposures may sometimes exceed these standards (Reinhardt and Ottmar 2004). Moreover, these exposures are usually many times the usual levels in ambient air which have been associated with a range of respiratory illnesses (Adetona et al. Accepted for publication, scheduled to be published August 2011; Reinhardt and Ottmar 2004). Although limited in number, results of studies of health effects among wildland firefighters also indicate their exposures may impact their health (Betchley et al. 1997b; Gaughan et al. 2008b; Liu et al. 1992b; Serra, Mocci, and Randaccio 1996b; Swiston et al. 2008). Ambient and indoor air woodsmoke exposure among the general population has also been linked with a variety of respiratory diseases (Delfino et al. 2008; Fullerton et al. 2008; Naeher et al. 2007; Orozco-Levi et al. 2006b; Sarnat et al. 2008).

One tool that may be useful for controlling exposure of wildland firefighters is the positive association of PM in woodsmoke to other potentially hazardous components of the mixture, particularly carbon monoxide (CO). This exposure characteristic may be so useful since exposure to CO is more easily monitored. While the correlation of the exposures to PM and CO among wildland firefighters has been shown to be relatively high (Adetona et al. Accepted for publication, scheduled to be published August 2011; Reinhardt and Ottmar 2004), the correlation has only been measured for time integrated exposures averaged over the duration of the workshift or work at the fireline. There is no study that has examined this relationship in real time. Such an investigation is important since both PM and CO may vary a lot under forest burn situations over small spatial and temporal resolutions depending on factors such as the instant wind direction relative to the wildland firefighter.

Furthermore, real time characterization of exposure to PM in woodsmoke among the firefighters allows for the investigation of peak exposures, and how much these may contribute to overall exposures of the firefighters. A pilot study conducted by our lab had indicated that wildland firefighter exposure to PM may be dominated by transient peak exposures (Edwards et al. 2005). Information about the contribution of peak exposures to total fireline or workshift exposure may also be useful for the determination of appropriate exposure control measures.

The current study was conducted primarily to characterize the relationship between exposures of wildland firefighters working at prescribed burns in the Southeastern United States to $PM_{2.5}$ and CO in real time. Secondarily, we attempted to characterize exposure to $PM_{2.5}$ in real time. Real time measurement enabled us to better investigate the effect of firefighter job task on $PM_{2.5}$ exposure. Previously, we had monitored exposure using time integrated samplers, which were inadequate for our current purpose since the firefighters working at the prescribed burns typically did more than one task at the fireline and over the duration of the workshift (Adetona et al. Accepted for publication, scheduled to be published August 2011).

METHODS

Study Location and Subject Recruitment

This study was conducted among the United States Forest Service (USFS) wildland firefighter crew at the Savannah River Site (SRS), where we had previously conducted exposure and health studies in 2003-05 and 2008-09 (Adetona et al. Accepted for publication, scheduled to be published August 2011; Naeher 201x). SRS is a National Environmental Research Park located in the southeastern coastal area of the United States with forests composed of 31% hardwood or mixed pine hardwood and 69% pine. The study, as the previous ones, was conducted during the dormant winter burn season, and was carried out between February and March 2011. Participation in the study was voluntary. We recruited six firefighters from the crew for each day when exposures were monitored, except the first day when five firefighters volunteered to participate. Subjects were recruited after the study was explained to them, and after they had signed the consent form. The study was approved by the University of Georgia Institutional Review Board for the inclusion of human subjects.

Exposure Monitoring

Monitoring of the exposures of the firefighters was restricted to the fireline, except when it was logistically impossible. Firefighters wore the monitors in their breathing zone. Real time $PM_{2.5}$ exposure was monitored with the Sidepak AM510 (TSI Inc., Shoreview, MN). The equipment is a size selective laser photometer designed to read the mass concentration of particulate matter. The Sidepaks used in this study were fitted with a 2.5 micron impactor, and set to log $PM_{2.5}$ concentrations every 30 seconds. They were zero calibrated before use each day monitoring was conducted. Logged data were retrieved from the equipment using the manufacturer's "Trakpro v. 4.4.0" software. Time integrated $PM_{2.5}$ was measured gravimetrically. Particles were collected using the BGI triplex cyclones (BGI Inc., Waltham, MA) already preloaded with Teflon filters with a 2.0 um pore size (Pall Corp., Ann Arbor, MI, USA). Air was drawn through the cyclones with the SKC Airchek 2000 (SKC Inc., Eighty Four, PA) sampling pumps. The system was designed to have a 50% aerodynamic cut-off point of 2.5 µm, with the pumps set to flow at 1.5 L/min. Pre and post-sampling flow rates of the pumps were measured with a Bios Dry Cal Defender 510 (Bios International, Butler, NJ, USA). The pre- and post-sample weights of the filters were determined using the Cahn C-35 microbalance. The time weighted average (TWA) particulate matter concentration was calculated as the amount of $PM_{2.5}$ collected per cubic meter (m^3) of air.

Real time exposure to CO was measured using Dräger Pac III single gas monitors (Draeger Safety Inc., Pittsburgh, PA) outfitted with CO sensors. The CO monitors were calibrated before the study at 0 and 50 ppm using pure nitrogen and 50 ppm CO gases (Calgaz, Air Liquide America Corp, Cambridge, MA). The CO monitors were also set to log data every 30 seconds.

The subjects were monitored while performing various tasks. These include lighting which involves the ignition of vegetative matter, holding which involves activities intended to keep the fire within pre-defined boundaries, and mop-up which involves the extinguishing of smoldering fire after the major burning phase. Other activities outside these major classifications were also engaged in by the firefighters. Information regarding the weather and fuel moisture was retrieved from the meteorological base on site.

Questionnaires, Time Activity Diary and Other Information

Since it was not practical to follow the firefighters throughout the prescribed burns, the subjects were given time activity diaries to complete during the burns. This was done to avoid recall bias which would have occurred if the firefighters were asked to complete the diaries after their workshifts. The time activity diaries were designed to be filled in every 30 minutes. Additionally, researchers were mostly able to monitor the firefighters through radio communications, take field notes to cross-check the data input by the subjects, and fill in the appropriate tasks for missing periods.

Subjects were administered questionnaires to collect data on possible confounding exposures such as tobacco smoke and vehicle exhaust.

Statistical Analysis

Percentage of total time of $PM_{2.5}$ exposure above 1 mg/m^3 and 3 mg/m^3, and corresponding percentage reduction in exposure were calculated for each person-day of exposure. Linear mixed effect models were used to analyze the effect of the job task of the firefighter on exposure to $PM_{2.5}$ and CO. Response variables were real time exposures (recorded every 30 seconds) averaged over the corresponding duration of job tasks and weighted in the models by the duration of time spent performing the job task. Linear mixed effect models were also used to test the effect of weather variables and fuel moisture on exposure to $PM_{2.5}$ and CO. Real time exposures (recorded every 30 seconds) were averaged over corresponding 1-hour periods since weather variables were collected hourly. Random subject effects were included in all the models to account for longitudinal within-subject correlation among the data, and random effects for the date of sample collection were included to account for possible heterogeneity in meteorological and burn conditions from day to day.

All statistical analyses were done using SAS version 9.1 (Cary, NC).

RESULTS

A total of 60 person-days of real time CO and 37 real time $PM_{2.5}$ exposure samples were collected from 15 firefighters over 10 burn days. The unadjusted geometric mean time weighted averages (TWA) for real time $PM_{2.5}$ and CO averaged over the length of time the firefighters spent working at the fireline, together with their sample sizes are presented in Table 1. The average length of time spent working at the fireline was 6.2 hours (range: 1.5 – 10.2 hours). The average ratio of real time to gravimetric $PM_{2.5}$ for the 25 pairs for which both measurements were valid was 1.40 (SD: 0.50).

Exposures of the firefighters differed according to their job tasks, and these results are presented in Figure 1 to 3. Since the subjects typically worked at more than one task during each workshift, real time data were used to calculate TWA exposure averaged over the duration of each work task. The data used in Figure 1 are the raw real time $PM_{2.5}$ measurements, while those used in Figure 2 (a subset of those used in Figure 1) are real time $PM_{2.5}$ data adjusted with the ratio of TWA real time $PM_{2.5}$ to TWA gravimetric $PM_{2.5}$ averaged over the time spent at the fireline in order to adjust for the overestimation or underestimation of the real time monitors. The effect of task on CO exposures is presented in Figure 3. The highest $PM_{2.5}$ exposures were measured when the firefighters were holding, followed by when they lighted, and then when they mopped up. The highest exposures to CO were also experienced when the firefighters were holding. The "other" category includes the period immediately before ignition, the period after ignition is completed and the period spent reviewing the burn, the use of chain saw, and the creation of a dozer line. Exposures to $PM_{2.5}$ and CO according to finer definitions of job tasks are presented in Table 2. Under these finer definitions holding and mop-up are classified based on whether they are done on foot, with the aid of a vehicle or on a mule; while the “other” task category is further refined. Results based on this classification show that wildland firefighters may experience significant amounts of exposure to $PM_{2.5}$ while the activity for the burn (AAR) is being reviewed, or when they use chain saws.

The percentage of the total times the subjects spent at the fireline with $PM_{2.5}$ (real time) exposures above the 3 mg/m^3 and 1 mg/m^3 thresholds are presented in Table 3. The percentage of time at the fireline when the firefighters experienced exposures above 3 mg/m^3 ranged between 2.6% and 40% accounting for 24% to 82% of the exposure. All the TWA $PM_{2.5}$ exposures fell below 1 mg/m^3 when exposures above 3 mg/m^3 were excluded. Exclusion of real time exposure data above 1 mg/m^3 further reduced TWA $PM_{2.5}$ exposures substantially. However, the percentage of time spent above the 1 mg/m^3 threshold was increased substantially with exposures above the threshold accounting for 12% to 56% of the total time spent by the firefighters at the fireline.

Temporal profiles of the concurrent exposures to $PM_{2.5}$ and CO are presented for 2 subjects in Figures 4 and 5. The graph indicates that exposures to both pollutants remain well correlated in real time.

Exposure was not affected by fuel moisture or any of the weather variables – temperature, relative humidity and wind speed.

DISCUSSION

Wildland firefighters are exposed to elevated levels of pollutants in woodsmoke, particularly to PM (Reinhardt and Ottmar 2004), which has been identified as the primary indicator of health effects of exposure to most combustion smoke, including the combustion of vegetation (Naeher et al. 2007). Managing such exposure is important for mitigating the vulnerability of the firefighters to consequent health effects. In order to develop effective exposure management strategies, adequate characterization of exposure is necessary. Such characterization should include monitoring of exposure in real time. Real time measurements of PM for example would afford accessibility to the temporal profiles of the PM exposure of the firefighter, and allow for a more complete analysis of the correlation between exposure to PM and other pollutants in woodsmoke. However, occupational exposure of wildland firefighters to PM in woodsmoke has been characterized based mostly on time integrated data, and data on real time exposure is lacking.

In the current study, $PM_{2.5}$ exposure was measured in real time among wildland firefighters working at prescribed burns in southeastern United States in order to: (a) determine the relative contribution of peak exposures to firefighter exposure, and (b) explore the correlation of $PM_{2.5}$ and CO in real time. Results indicate that peak exposures, which were mostly transient, dominated the $PM_{2.5}$ exposure of the wildland firefighters. The peak exposures (> 3 mg/m^3) contributed mostly more than 50% of the exposure, but accounted for mostly less than 20% of the exposure time. Previous results from our laboratory had shown similar results (Edwards et al. 2005), and indicated that real time particulate matter monitors with set thresholds could be used as a tool to inform wildland firefighters about when to use respiratory protection. Implementation of such a strategy would contribute to a substantial reduction in exposure among wildland firefighters even at a relatively high threshold of 3 mg/m^3. Lowering the threshold further may result in substantial time cost as results for the threshold of 1 mg/m^3 presented in Table 3 show.

Real time results suggest that firefighters in this study rarely had particulate matter exposures above the ACGIH's $PM_{3.5}$ TLV of 3 mg/m^3, but this was certainly exceeded for one firefighter with a real time $PM_{2.5}$ exposure of 3.8 mg/m^3 and a corresponding gravimetric measurement of 3.3 mg/m^3 measured over an 8-hour period. None of the firefighters had CO exposure above OSHA's PEL of 50 ppm. The excursion short term exposure limit for CO of 75 ppm which has been recommended for wildland firefighters (Reinhardt and Ottmar 2004) was exceeded on just one occasion during sampling. The recommended excursion STEL for $PM_{3.5}$, which is 9 mg/m^3, was exceeded on one sampling day each for three firefighters. Two of the firefighters who exceeded the excursion STEL for 54 and 16 minutes were performing holding tasks when the exceedances occurred. The other firefighter exceeded the $PM_{3.5}$ excursion STEL for 11 minutes and was lighting. The only firefighter exceeding the excursion STEL for CO was also holding when this exceedance occurred. However, it should be noted that the determination of short term exposure to $PM_{2.5}$ based on the real time aerosol monitor may have been affected by instrumental error. The real time aerosol monitor, SidePak AM510, uses light scattering technology to determine the mass concentration of particles in air, and is calibrated against a gravimetric reference, the Arizona test dust. The instrument were run with the default factory calibration factor which assumes the same size distribution, density and refractive index as the reference Arizona test dust for the woodsmoke particles to which the wildland firefighters in this study were exposed. This could have resulted in overestimation or underestimation of the exposures depending on the characteristics of the woodsmoke particles.

Wildland firefighter exposure differed across different job tasks. The firefighters had the most exposure to both CO and $PM_{2.5}$ when they were holding. The results corroborate the expectations of the firefighters that this job task exposes them to more woodsmoke. Unlike lighting which is carried out in patterns that are designed to keep the firefighters upwind of the smoke, holding is often carried out downwind of the smoke to prevent the fire from being carried by the wind outside the burn boundary. Exposure studies during wildfires and prescribed burns in Western United States have also indicated that exposures may be higher among firefighters who are assigned holding task (Reinhardt and Ottmar 2004). Exposure during mop-up which is conducted mostly during the smoldering phase of a burn is similar to the exposures of the firefighters when they are lighting.

Results in older studies have shown time integrated gravimetric $PM_{2.5}$ exposures to be well correlated with CO exposures (Reinhardt and Ottmar 2004). Temporal profiles of concurrent exposures of subjects in this study to $PM_{2.5}$ and CO, as exemplified by Figures 4 and 5, indicate that the two pollutants remain correlated over smaller temporal resolutions. This piece of information is important since CO monitoring is easier, less cumbersome and could therefore be an ideal surrogate for estimating exposure to $PM_{2.5}$.

We were only able to monitor a convenience sample of wildland firefighters for this study. Consequently our measurements may have been biased by the more likely selection of firefighters who were more concerned about elevated levels of exposure to woodsmoke. The firefighters could also have altered their behavior due to the presence of the researchers at the fireline resulting in the modification of their exposure away from the typical values. However, we did not think that these would have occurred as most of the members of the firefighting crew stationed at SRS had participated at least once during the course of the study. Furthermore, wildland firefighting demands a lot of professionalism, and requires a delicate balance between achievement of work objectives and safety. We were also restricted to one study site during the study, and our results may not be generalizable to territories distant from this study site. However, we expect that results, if exposure studies were conducted at prescribed burns in other areas, would be similar to those in this study, especially with regards to the contribution of peak exposures to overall exposures, and how exposures differed across job tasks. The results for exposures according to tasks in this study were similar to those measured in Western United States, with exposures for persons performing holding tasks being higher than exposures for persons lighting or mopping up. As in this study, exposures were similar for persons performing the last two tasks. Finally, the ratio between real time and gravimetric $PM_{2.5}$ was not constant and varied within and between monitors. This may have been due to various factors such as the variation of the composition of the vegetation that was lighted between and within burns, and influence of the task being carried out by the firefighter. However, the ratio also varied within each of the tasks. Nevertheless, results were similar when the effect of task on exposure was analyzed with $PM_{2.5}$ concentrations adjusted for the real time to gravimetric concentration ratios (Figure 2), compared with when the analysis was done with the raw real time $PM_{2.5}$ data (Figure 1).

CONCLUSION

We characterized exposure to $PM_{2.5}$ in real time and obtained results that could be useful for managing wildland firefighter exposure to woodsmoke. We established that transient peak exposures often contributed significantly to overall exposure. Such information could be exploited to reduce exposures of the firefighters by a substantial amount without compromising a lot of time or inconveniencing the firefighter for too long. The data also indicated that CO and particulate matter were correlated over smaller temporal resolutions. This supports the conclusion based on correlation observed in studies involving exposures averaged over the workshift that each of the two may be used as a surrogate of exposure to the other pollutant in health studies as was done in a study in British Columbia (Swiston et al. 2008), or with regards to efforts designed to control exposure. Finally, we determined that exposures differed across tasks with persons performing holding tasks being the most exposed firefighters.

RECOMMENDATIONS

Currently available respiratory protection may be impractical for use throughout the duration of a firefighting workshift of a wildland firefighter for various reasons (Reinhardt and Ottmar, 2004). However, the National Wildfire Coordinating Group (NWCG), as one of its recommended measures to control woodsmoke exposure among wildland firefighters proposed that fire managers develop an effective respiratory protection program for certain firefighting situations (Sharkey, 1997). The deployment of respiratory protection when certain threshold of exposure is exceeded (3 $\mu g/m^3$ in the analysis for this study) could satisfy the NWCG recommendation while also eliminating the need to wear such protection for the whole duration of the firefighting workshift, and restricting such deployments to a limited proportion of the workshift.

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Table 6.1: Unadjusted geometric mean of gravimetric $PM_{2.5}$, real time $PM_{2.5}$ and CO averaged over all person-day measurements that were valid.
LCL: 95% Lower class limit
UCL: 95% Uower class limit

	Gravimetric $PM_{2.5}$ (µg/m^3)	Real Time $PM_{2.5}$ (µg/m^3)	CO (ppm)
Mean	608	920	3.9
LCL	481	779	3.2
UCL	767	1089	4.5
N	41	37	58

Table 6.2: Geometric mean according to job task based on a more refined classification with holding and mop-up being sub-divided according to the means by which they are done for CO and $PM_{2.5}$

CO (ppm)

	Others - activities pre-ignition	Chain Sawing	Holding on mule	Holding with vehicle	Lighting	Mop-up on foot	Mop-up on mule	Mop-up with vehicle	AAR - post-ignition burn review	Others - activities post-ignition
Mean	3.9	7.9	7.3	7.4	6.8	6.4	6.1	6.6	5.9	5.1
LCL	3.5	5.8	6.7	6.6	6.4	4.9	5.1	5.9	5.4	4.6
UCL	4.3	10.1	8.0	8.2	7.2	7.9	7.1	7.3	6.3	5.5
N	32	2	11	9	44	4	8	11	42	32

PM2.5 (µg/m^3)

	Others - activities pre-ignition	Holding on mule	Holding with vehicle	Lighting	Mop-up on foot	Mop-up on mule	Mop-up with vehicle	AAR - post-ignition burn review	Others - activities post-ignition
Mean	50	1556	1622	914	601	443	716	358	159
LCL	26	1522	2044	481	2162	720	753	198	86
UCL	17	769	904	315	470	274	367	127	56
N	27	10	7	26	2	5	9	24	25

Table 6.3: Individual $PM_{2.5}$ exposures and the contribution of exposures above 3 mg/m^3 and 1 mg/m^3 to overall exposure in individual exposures: data is shown for all real time $PM_{2.5}$ data collected during the study period.

		TWA $PM_{2.5}$ including all data points		TWA PM2.5 excluding exposure incidences > 3 mg/m^3				TWA PM2.5 excluding exposure incidences > 1 mg/m^3			
Date	ID	Duration (min)	$PM_{2.5}$ Exposure	Duration (min)	$PM_{2.5}$ Exposure	%age of time > 3 mg/m^3	%age of exposure > 3 mg/m^3	Duration (min)	$PM_{2.5}$ Exposure	%age of time > 1 mg/m^3	%age of exposure > 1 mg/m^3
2/13/2011	8	322	509	302	204	6	59.9	282	96	12	81.2
	10	335	441	323	245	4	44.3	297	102	11	76.9
2/15/2011	3	512	870	476	403	7	53.7	415	229	19	73.6
	8	365	1480	309	560	15	62.1	248	285	32	80.7
2/17/2011	4	303	512	292	351	3	31.5	257	153	15	70.2
	5	301	1079	267	479	11	55.6	220	208	27	80.7
	8	251	576	245	441	3	23.5	205	177	19	69.3
	9	418	567	398	318	5	44.0	359	161	14	71.7
	10	337	851	310	339	8	60.2	275	148	19	82.5
2/27/2011	8	269	616	256	354	5	42.5	228	179	15	70.9
	9	275	1518	220	609	20	59.9	169	199	39	86.9
	10	267	1101	237	322	11	70.7	210	132	21	88.0
	11	270	796	250	384	7	51.8	216	149	20	81.2
	12	263	664	250	354	5	46.7	223	189	15	71.5
3/3/2011	5	503	833	466	441	7	47.0	394	199	22	76.2
	8	494	3800	299	681	40	82.1	216	223	56	94.1
	10	292	742	269	352	8	52.5	233	130	20	82.4
	16	323	1497	273	694	16	53.6	192	233	41	84.4
	17	425	1260	372	596	12	52.7	288	251	32	80.0
3/4/2011	8	222	637	211	409	5	35.8	181	194	19	69.6
	9	250	1001	225	570	10	43.0	169	186	32	81.5

	16	577	764	539	469	7	38.6	447	223	22	70.8
	17	580	577	552	373	5	35.4	476	153	18	73.5
3/8/2011	3	430	1796	339	625	21	65.2	261	270	39	85.0
	8	392	682	365	304	7	55.5	324	124	17	81.8
	9	264	975	239	254	10	73.9	216	86	18	91.2
	17	279	399	271	246	3	38.4	247	103	12	74.1
3/9/2011	5	194	873	174	293	11	66.5	154	106	21	87.9
	8	90	2276	60	678	33	70.2	44	244	51	89.3
	16	125	1287	109	641	13	50.2	81	197	36	84.7
	17	200	1770	167	423	17	76.1	141	145	30	91.8
3/12/2011	16	465	704	437	362	6	48.6	384	177	18	74.9
	19	450	631	424	315	6	50.0	383	166	15	73.6
	20	454	1208	388	517	15	57.2	315	224	31	81.4
3/13/2011	16	518	1082	448	193	14	82.2	422	79	19	92.7
	19	525	518	507	313	4	39.6	436	103	17	80.1
	20	454	2719	327	645	28	76.3	244	214	46	92.1

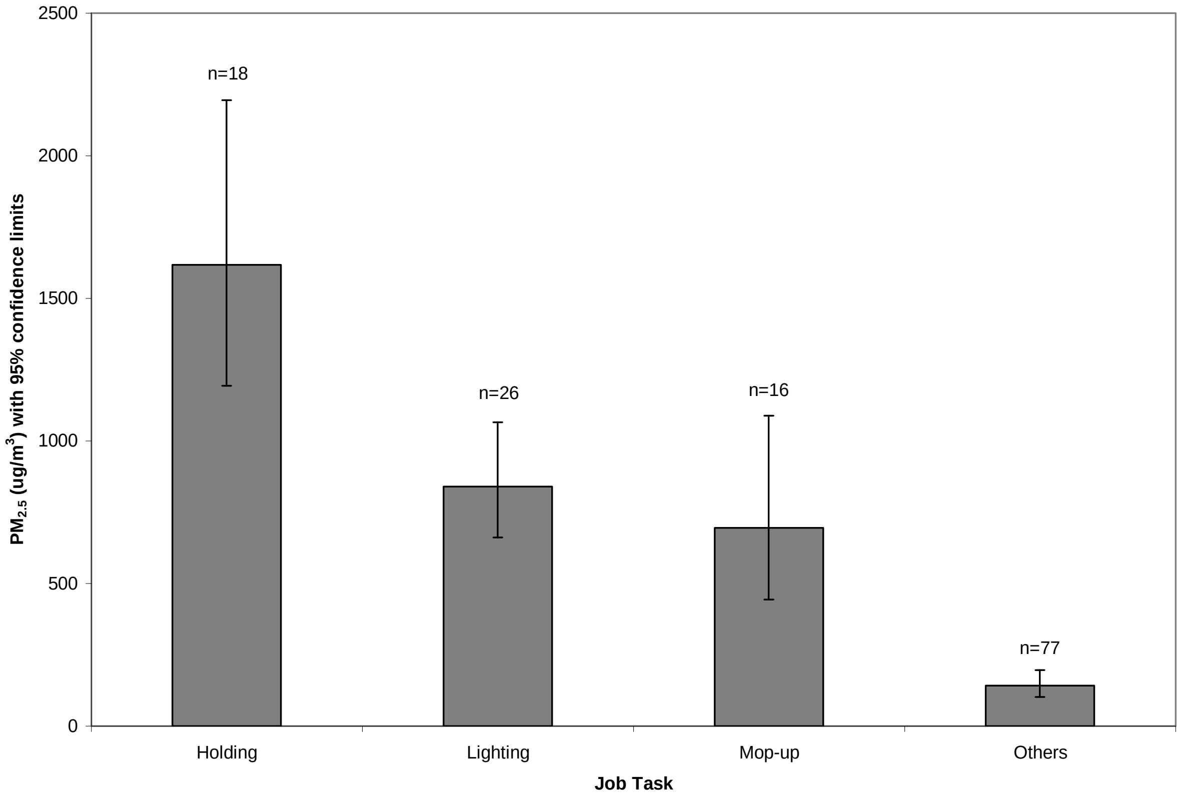

Figure 6.1: Raw real time $PM_{2.5}$ exposures according to different tasks of firefighters – holding, lighting, mop-up, and others: the "other" category includes the period immediately before ignition, the period after ignition is completed and the burn activity is being reviewed, the use of chain saw, and the creation of a dozer line. Raw real time $PM_{2.5}$ data was used for the analysis. Holding is significantly higher than the other types of tasks ($p<0.05$).

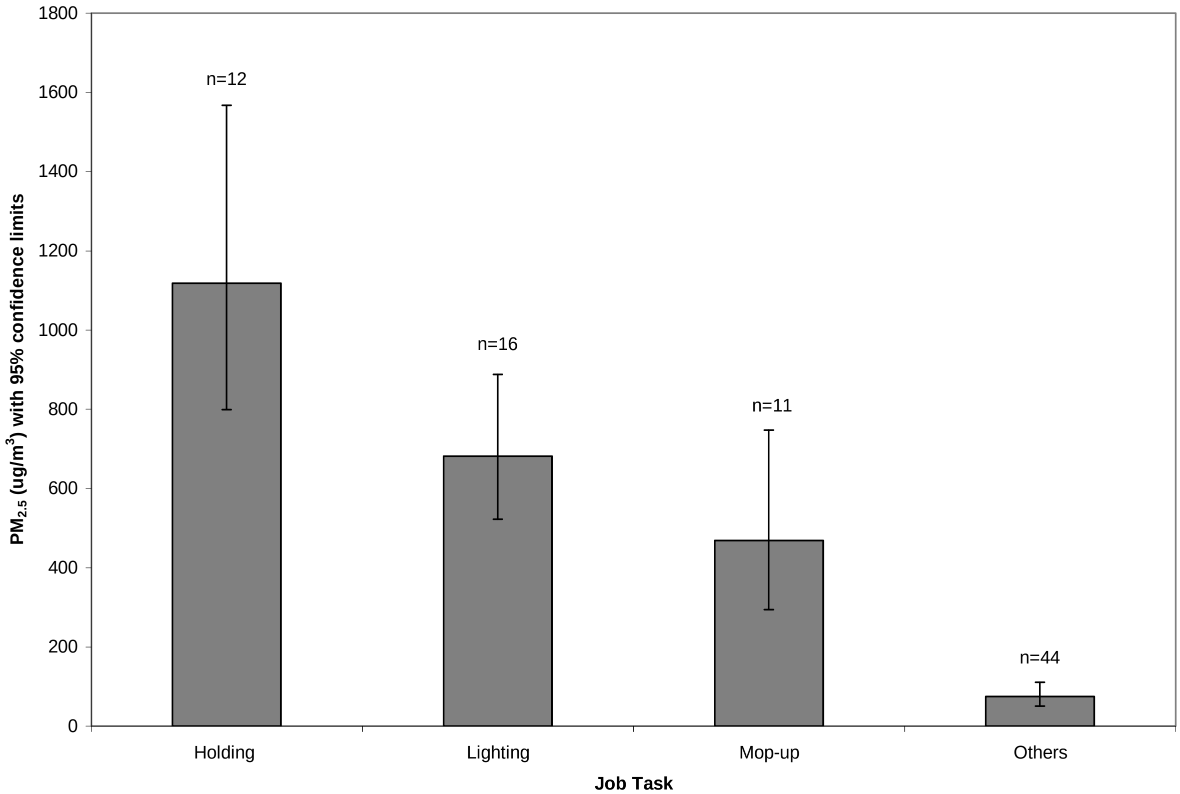

Figure 6.2: Real time-gravimetric ratio adjusted real time $PM_{2.5}$ exposures according to different tasks of firefighters – holding, lighting, mop-up, and others: the "other" category includes the period immediately before ignition, the period after ignition is completed and the burn activity is being reviewed, the use of chain saw, and the creation of a dozer line. Real time $PM_{2.5}$ data adjusted for the real time to gravimetric concentrations was used for the analysis. Holding is significantly higher than the other types of tasks ($p<0.05$).

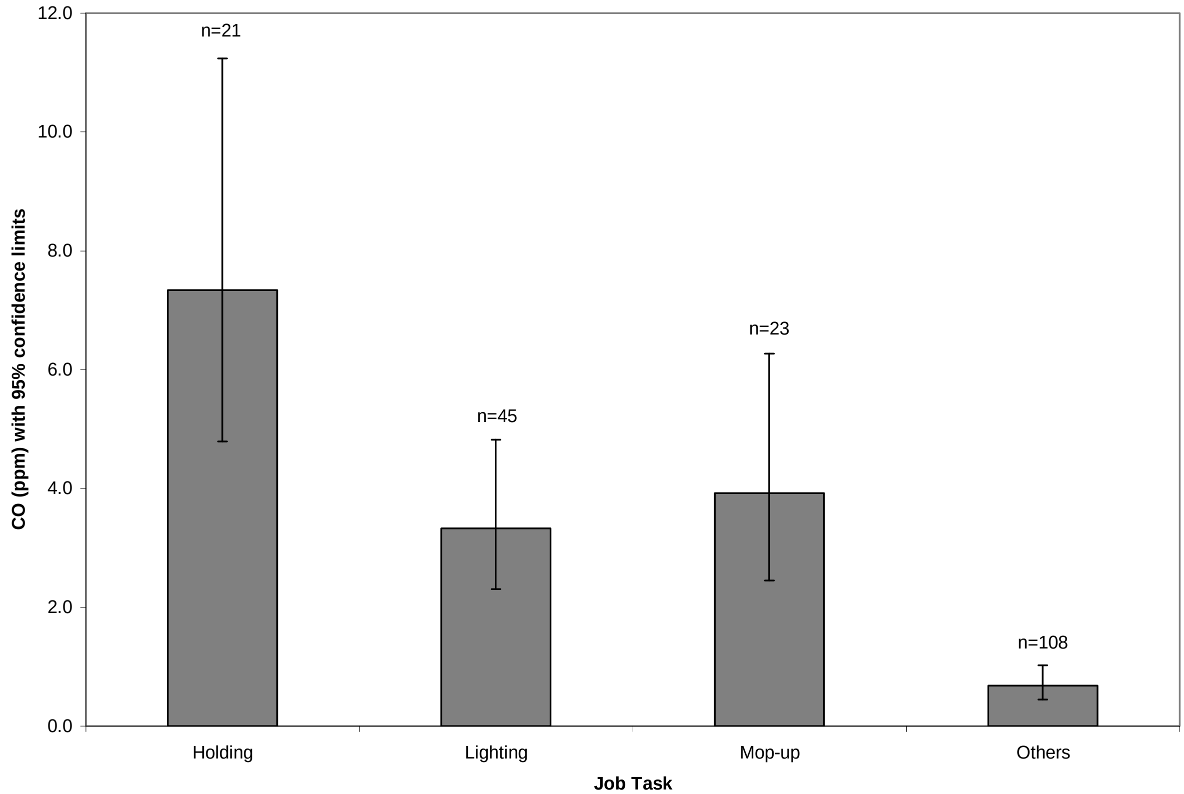

Figure 6.3: CO exposures according to different tasks of firefighters – holding, lighting, mop-up, and others: the “other” category includes the period immediately before ignition, the period after ignition is completed and the burn activity is being reviewed, the use of chain saw, and the creation of a dozer line. Holding is significantly higher than the other types of tasks ($p<0.05$).

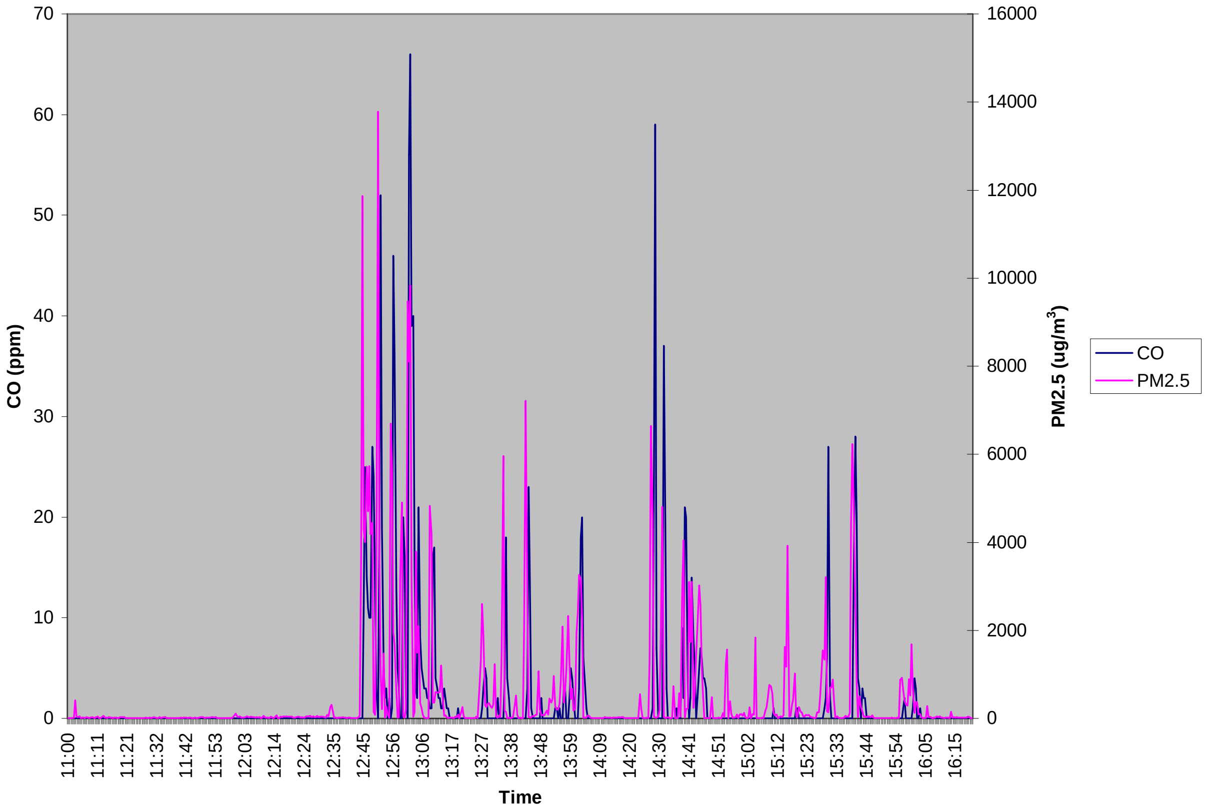

Figure 6.4: Temporal profiles of real time CO and $PM_{2.5}$ exposures for one subject on the first day of sampling

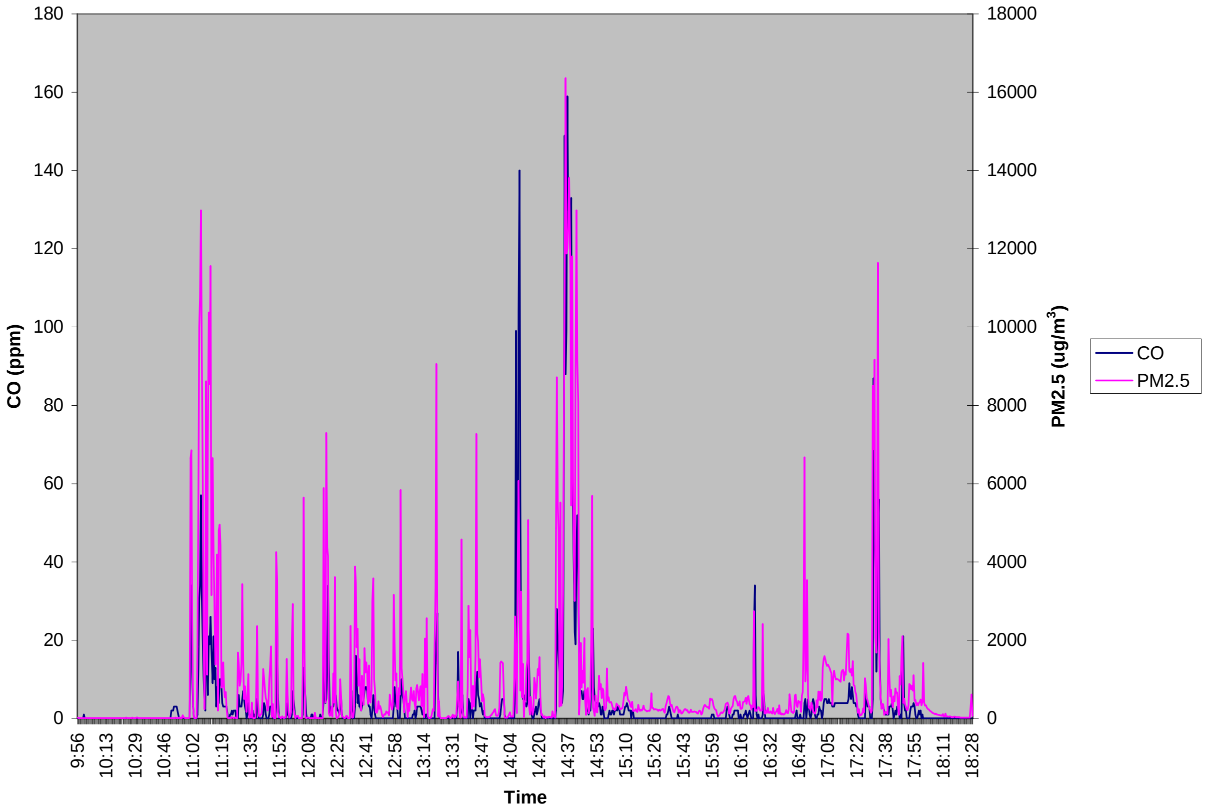

Figure 6.5: Temporal profiles of real time CO and $PM_{2.5}$ exposures for one subject on the second day of sampling

CHAPTER 7

SUMMARY AND CONCLUSION

Woodsmoke is emitted from the combustion of vegetative matter. It is a complex mixture of hundreds of gaseous and solid substances, many of them hazardous to human health (Naeher et al. 2007). Exposure to woodsmoke occur in numerous situations, with elevated exposures being more pervasive in the indoor environments in developing countries (Fullerton, Bruce, and Gordon 2008) and during wildfire events (Emmanuel 2000). Occupational exposure to elevated levels of woodsmoke does occur among wildland firefighters (Reinhardt and Ottmar 2004).

A few studies have investigated woodsmoke exposure among wildland firefighters and the chief inhalation hazard in this exposure situation has been identified to be CO and particulate matter (Reinhardt and Ottmar 2004). However, most of the studies have been done in Western United States (Materna et al. 1992; Reinhardt and Ottmar 2004) with data lacking for other regions of the country where vegetation and weather, which may affect exposures, are different. Other gaps regarding woodsmoke exposure among wildland firefighters remain. These include the relationship between CO and $PM_{2.5}$ over smaller temporal resolutions, and characterization of exposure to particulate matter in real time. Such information would be important for controlling occupational woodsmoke exposure among wildland firefighters, and is especially relevant since the USFS is currently seeking to develop occupational exposure limits for wildland firefighting.

Furthermore, studies of health effects among wildland firefighters are mostly limited to the effect of woodsmoke exposure on lung function. One study reported across shift declines in lung function (Betchley et al. 1997). However, comparisons were not made against days when the firefighters did not work at fires, raising the possibility that such findings might have been confounded by the natural circadian patterns associated with lung function. Furthermore, studies on other health end points are lacking.

In order to fill in some of the identified gaps regarding occupational woodsmoke exposure and associated health effects among wildland firefighters, we monitored exposure among a crew of USFS wildland firefighters. We also studied the effect of exposure on lung function and oxidative stress among the same firefighting crew.

Wildland Firefighter Exposure to Woodsmoke

The objectives of this study were to measure the exposure of wildland firefighters to woodsmoke using $PM_{2.5}$ as the surrogate of exposure. As stated previously, particulate matter has been identified as one of the two chief inhalation hazards of woodsmoke exposure among wildland firefighters. Furthermore, it was sought to determine the factors that may be important for firefighter exposure, whether the firefighters could qualitatively estimate their exposures, and the relationship between exposures to CO and $PM_{2.5}$ averaged over the workshift. The study was conducted among a USFS firefighter crew located at the Savannah River Site, SC in southeastern United States. Consequently, contributions from the study include the provision of exposure data for a region for which they are lacking. Also, exposure monitoring was done while the firefighters worked at prescribed burns. Earlier studies had reported that there were higher exposures at prescribed burns compared to wildfires regardless of type (Reinhardt and Ottmar 2004).

The geometric mean $PM_{2.5}$ exposure calculated from a linear mixed effect model adjusted for firefighter task, wind speed, length of work-shift, and size of burn was 280 $\mu g/m^3$ (95% CL =

140, 557 μg/m^3, n = 177) for burn day samples, and 16 μg/m^3 (95% CL = 10, 26 μg/m^3, n = 35) for non-burn day samples. Workshift TWA $PM_{2.5}$ above 1000 μg/m^3 was experienced in 11% (n = 18) of all samples included in data analysis, while exposure was above 2000 μg/m^3 and 2500 μg/m^3 in 3% (n = 5) and 1% (n = 2) of these samples respectively. There was a significant linear trend of increasing personal $PM_{2.5}$ exposure being observed at higher levels of self-assessed exposure ($p < 0.0001$). Lastly, TWA $PM_{2.5}$ was correlated with concurrently measured TWA CO (Pearson Correlation Coefficient estimate, r = 0.79; CLs: 0.72, 0.85).

Although exposures in this study seem to be lower than in studies conducted in the Western United States, the results indicate that the wildland firefighters in this study also experienced elevated exposures. Their exposures were many times higher than the ambient air standard and well above the background levels, sometimes approaching the recommended ACGIH TLV of 3 mg/m3 for respirable particles. The relationship between firefighter estimation to woodsmoke and measured $PM_{2.5}$, and the relatively high correlation between CO and $PM_{2.5}$ suggest that these tools could at least be used for the estimation of exposure in epidemiological studies. The correlation between CO and $PM_{2.5}$ may also be exploited in exposure control.

Woodsmoke Exposure Associated Lung Function Changes

Various studies of wildland firefighters have reported across fire season declines in lung function (Liu et al. 2005; Rothman et al. 1991), and significantly lower lung function measures were observed for firefighters compared to policemen in another study (Serra, Mocci, and Randaccio 1996). One study that reported across shift declines in FEV_1 and FVC when firefighters fought fires did no comparisons of the changes with days when the firefighters did not work at fires. Such results could have been confounded by the normal circadian patterns associated with lung function (Borsboom et al. 1999).

Therefore, we studied and compared lung function changes on burn and non-burn days. We also sought to determine the effects of cumulative exposure during the season, measured as cumulative number of exposure days, on lung function. Spirometry measurements were collected from wildland firefighters working at prescribed burns at the Savannah River Site, SC pre- and post-shift on burn and non-burn days during the dormant winter burn seasons of 2003-04.

Declines across workshift were observed for mean individual FVC and FEV_1, but changes in both measures on burn days were not significantly different from those on non-burn days. However, each additional day of working at a prescribed burn, at any given point during the burn season, was associated with declines of 24ml in pre-shift FVC and 24 ml in post-shift FEV_1 ($p<0.01$).

The results in this study highlight the importance of controlling for natural diurnal patterns when studying lung function. They also indicate possible longer term effects of woodsmoke exposure on lung function in wildland firefighters.

Across Shift Changes in 8-OHdG

As already reported, wildland firefighters are exposed to elevated levels of particulate matter in woodsmoke. Particulate matter has also been identified as the chief inhalation hazard in woodsmoke. Induction of toxicity by particulate matter is thought to involve oxidative stress and inflammation (Li et al. 2002; Schins et al. 2004). Woodsmoke particles contain free radicals and are capable of generating ROS within the cells (Leonard et al. 2007; Leonard et al. 2000). Results of studies also show that the particles could induce oxidative stress measurable as increased DNA damage in lung cell lines (Danielsen et al. 2009), and in rats (Danielsen et al. 2010). Measurable increases in biomarkers of oxidative stress and inflammation after exposure to woodsmoke have also been observed in human experiment studies (Barregard et al. 2008; Barregard et al. 2006). However, only recently have these end-points been studied among the general population outside of controlled experiments. Swiston et al. investigated the effect of woodsmoke exposure on inflammation among wildland firefighters and observed across-shift increases in pro-inflammatory cytokines, IL-6 and IL-8 (Swiston et al. 2008). However, there has been no equivalent study regarding oxidative stress.

In this study, urine samples were collected from wildland firefighters working at prescribed burns at the Savannah River Site, SC pre- and post-shift on burn and non-burn days during the dormant winter burn seasons of 2004. The samples were analyzed for 8-OHdG and MDA, and statistical analyses were conducted to test whether there were any significant across shift changes in the levels of these biomarkers, and whether the levels or across shift changes in these biomarkers were associated with levels or across shift changes in concurrently measured levoglucosan. Levoglucosan, a product of wood pyrolysis, is present in woodsmoke, absorbed into the body, and excreted in urine. The effect of the length of firefighting career on across shift changes in 8-OHdG and MDA was also tested. Since age correlated with the length of firefighting career, both were included separately and together in the models used for the analyses.

Overall, there was no significant across shift changes in 8-OHdG and MDA. However, there was a significant increase ($p = 0.04$) of 0.79 log units of creatinine corrected 8-OHdG from pre- to post-shift among the 3 subjects who had worked as wildland firefighters for 2 years or less when only the number of firefighting years was included as a covariate in the model. In contrast, there was a change of -0.90 ($p = 0.03$) for the 3 subjects who had worked as firefighters for 10 years or more. Changes for subjects who had worked 3-5 years ($n = 5$) or 5-10 years ($n = 5$) were also negative but insignificant at $p = 0.05$ (Figure 1). Creatinine corrected 8-OHdG and levoglucosan in the post-shift samples were correlated ($\rho_{est} = 0.24$; $p = 0.04$).

Results suggest that across shift changes in the excretion of 8-OHdG could depend on the age of the subject or the number of years spent working as a firefighter, with more observable increases across shift for firefighters who had spent the least number of years at the job. We also observed relatively high levels of 8-OHdG in the subjects' urine samples compared to data reported in the literature, suggesting the firefighters were experiencing sustained increase in oxidative DNA damage during the burn season.

Characterization of Exposure to CO and $PM_{2.5}$ in Real Time

The objectives of this study were to characterize the exposures of wildland firefighters to CO and $PM_{2.5}$ in real time, and to explore the correlation between exposures to both pollutants in real time. The correlation between CO and $PM_{2.5}$ is important since it may be exploited as an exposure control or assessment tool. Correlation estimated from TWA exposures averaged over larger durations such as firefighter workshift may be inadequate as it may obscure differential variations that may occur in the pollutants over smaller periods. Temporal profiles of the concurrent exposures to $PM_{2.5}$ and CO indicated that both pollutants were closely correlated with each other over smaller temporal resolutions. This further indicates that the relationship between exposures to both pollutants in woodsmoke could be exploited for exposure control or in epidemiological studies. Therefore, the more easily monitored CO could be used in both exposure assessment and epidemiological studies as a surrogate for exposure to $PM_{2.5}$, which is thought to be the best single indicator of the health effects of combustion sources.

In this study, it was observed that exposures of the wildland firefighters differed according to their job tasks ($p<0.01$). Firefighters conducting "holding" had the highest exposures to CO and $PM_{2.5}$. Firefighter exposures were also dominated by peak exposures. The percentage of time at the fireline spent above 3 mg/m^3 ranged between 2.6% and 40% accounting for 24% to 82% of the exposure. Setting a threshold exposure at which to activate a respiratory protection action may also be an effective exposure control strategy with relatively minimal loss of time, and less inconveniencing of the firefighter. The wearing of respirators during the relatively short periods when the threshold is exceeded would reduce particulate matter exposure substantially.

Conclusion

The conduct of a study among wildland firefighters in Southeastern United States provided the opportunity to fill the data gap regarding wildland firefighter occupational woodsmoke exposure as compared to the western region of the country. Similar to prior studies conducted in Western United States, it was found that wildland firefighters are exposed to elevated levels of particulate matter in woodsmoke, with exposure in some instances approaching or exceeding recommended occupational standards. In addition to measuring time integrated exposure, we monitored firefighter exposure to $PM_{2.5}$ in real time, and obtained results that could be useful for controlling exposure. It was observed that transient peak exposures often dominated firefighter exposure to woodsmoke, corroborating results of a pilot study that had been done from our lab with fellow collaborators (Edwards et al. 2005). The use of a real time aerosol monitor set to alarm at certain threshold could be used to inform temporary usage of respiratory protection (Edwards et al. 2005) without inconveniencing the firefighter for long continuous periods. Regarding the correlation between CO and $PM_{2.5}$, similar results to those reported for studies in Western United States were observed. Correlation between time weighted averages of CO and $PM_{2.5}$ was relatively high. However, the association between occupational exposures to both pollutants in woodsmoke in real time was also explored. Concurrent temporal profiles of exposures to CO and $PM_{2.5}$ indicate that exposures to both pollutants in woodsmoke remain well correlated over smaller temporal resolutions. A good correlation between pollutants in woodsmoke implies that the more easily measured pollutant, such as CO, can be used as a surrogate for the exposure to the other pollutants. Such results could be usefully employed in epidemiological studies (Swiston et al. 2008), or as tools for controlling exposures.

Although, acute effects measurable as across shift changes were not observed in the studies of the effect of occupational woodsmoke exposure on lung function and oxidative stress, accumulated exposure measured as the cumulative number of firefighting days in a season was associated with a decline in lung function. The relatively high levels of urinary 8-OHdG measured in the urine samples of the firefighters also suggest sustained oxidative stress in the firefighters for the period of occupational exposure through the burn season. Results of both studies highlight the need to extend the investigation of health effects of occupational woodsmoke exposure among wildland firefighters to the longer term. Although across shift changes after occupational exposure to woodsmoke, such as was observed for pro-inflammatory cytokines among a group of wildland firefighters in British Columbia are very informative, knowledge regarding how these biomarkers of effects change with time in wildland firefighters relative to comparable non-exposed groups would inform about the possible longer term effects of woodsmoke exposure.

The results of the studies presented in this dissertation are particularly timely because the United States Forest Service recently set up an expert panel tasked with the development of occupational exposure limits for wildland firefighting. They also have implications for other elevated woodsmoke exposure situations, such as in the indoor environment in developing countries where residential supply of energy is still largely dependent on the combustion of wood. Chronic exposure to woodsmoke in this situation may result in sustained decrements in lung function, and persistent elevation in the levels of oxidative damage within the body, most likely in the airways. Increase in exhaled breath MDA in human subjects after woodsmoke exposure was observed in a chamber experiment study (Barregard et al. 2008). Such responses may presage future developments of diseases. Hence, longitudinal investigations of changes in these health end points would provide a more definitive platform for the determination of associations of woodsmoke exposure with chronic diseases.

Future Research

As stated above, longitudinal studies with the use of a comparable population are needed to study the longer term effects of occupational woodsmoke exposure among wildland firefighters. There is also need to investigate more health end points. This is beginning to be done, with in a study in British Columbia investigating the effect of woodsmoke exposure on inflammation, and the study presented in Chapter 5 of this dissertation focusing on oxidative stress. Our laboratory had collected dried blood spot samples concurrently with exposure measurements during the exposure study presented in Chapter 6. These samples are currently banked for future analysis of pro-inflammatory cytokines. Longitudinal studies may be more easily done if this less invasive method of blood sample collection proves useful for observing across shift changes associated with woodsmoke exposure.

Finally, investigation of the relationship between a good biomarker of woodsmoke exposure and responses, such as inflammation that has proven useful for the investigation of acute health effects of woodsmoke exposure (Swiston et al. 2008) would more definitively establish whether there is a link between woodsmoke exposure and the health effect being studied. However, compounds that may be used as biomarkers of woodsmoke exposure are still being evaluated (Simpson and Naeher 2010). Some of these studies have been conducted by our laboratory in conjunction with other collaborators (Naeher and Barr 201x: in prep; Neitzel et al. 2008) with urinary methoxyphenols showing promise as a biomarker of woodsmoke exposure (Neitzel et al. 2008).

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APPENDICES

APPENDIX A: STUDY CONSENT FORM

Consent Form #1: Occupational woodsmoke exposure and respiratory effects among wildland firefighters working at prescribed burns, Savannah River Site, SC, 2003-05

Worker exposure and respiratory effects of particulate matter during prescribed burns: CONSENT FORM #1

I, _________________________________ agree to take part in the research study titled **"Worker exposure and respiratory effects of particulate matter during prescribed burns"** conducted by Dr. Luke Naeher from the Department of Environmental Health Science at the University of Georgia [706-227-3854]. I understand that I do not have to take part if I do not want to. I can stop taking part without giving any reason, and without penalty. I can ask to have all of the information about me returned to me, removed from the research records, or destroyed.

The reason for this study is to obtain information on my exposure to air pollution from prescribed forest burns in southeastern US forests.

If I volunteer to take part in this study, I will be asked to do the following things:

1) Answer questions about my personal and work activities that might affect my exposure to air pollution and other chemicals in the environment.
2) Wear personal air sampling equipment for 8-12 hours each work day for 5 weeks.
3) Do a breathing test before and after each work day for 5 weeks.
4) If I am willing, give a urine sample (approximately 3 tablespoons) at the start and end of each day I wear personal air sampling equipment. Part of my urine samples will be sent to the Centers for Disease Control and Prevention (CDC), National Center for Environmental Health and part will be sent to the University of Washington, Seattle, WA, USA, where the amounts of some chemicals related to air pollution will be measured in the urine samples
5) If I am willing, give a blood sample (venous draw of approximately 2 tablespoons) at the start and end of no more than 5 select work shifts.
6) If I am willing, a small amount of my blood and urine will be stored for analysis of measures of exposure or effect in the future.

I will receive a UGA research study t-shirt or equivalent at the end of the study as compensation for being in this study.

My blood will not be tested for HIV-AIDS. I understand these questions and air, blood, and urine tests are not for diagnostic purposes and are not going to be used to screen for drugs. If I have questions about my test results I should see a physician. I understand that I do not have to give a blood sample and I can still be in this study even if I choose not to give blood. The benefits for my workplace and community are that the air pollution, blood and urine contaminant data may help leaders in occupational and public health agencies reduce elevated occupational and environmental exposures to me and others in my workplace and community.

The risks of drawing blood from my arm include the unlikely possibilities of a small bruise or localized infection, bleeding, dizziness or nausea and fainting. These risks will be reduced in the following ways: my blood will be drawn only by a qualified and experienced person who will follow standard sterile techniques, who will observe me after the small needle is withdrawn, and who will apply pressure to the blood draw-site.

Any information that is obtained in connection with this study and that can be identified with me will remain confidential and will be disclosed only with my permission or as required by law. I will be assigned an identifying number and this number will be used on all air monitoring and urine samples I provide and questionnaires I fill out. Urine samples sent to CDC or UW-Seattle will have this same identifying number on them.

The investigator will answer any further questions about the research, now or during the course of the project (706-542-2454). Questions can also be directed to Dr. Allison Stock at CDC (404-498-1034).

I understand that I am agreeing by my signature on this form to take part in this research project and understand that I will receive a signed copy of this consent form for my records.

_________________________________   _________________________________

Signature of Investigator   Date   Signature of Participant   Date

Additional questions or problems regarding your rights as a research participant should be addressed to Chris A. Joseph, Ph.D. Human Subjects Office, University of Georgia, 606A Boyd Graduate Studies Research Center, Athens, Georgia 30602-7411, USA; Telephone (706) 542-3199; E-Mail Address IRB@uga.edu

Consent Form #2: Consent to bank blood and urine samples, 2003-05

Worker exposure and respiratory effects of particulate matter during prescribed burns

Consent form #2: Consent to bank blood and urine This form requests you to allow us to store a portion of your blood and urine sample in the University of Georgia, Department of Environmental Health Science Laboratory in Athens, Georgia, USA or at the CDC so that it could be used for possible future studies. These samples will be stored with the same identifying number used to identify the urine samples for the CDC and UW-Seattle labs. No study will be performed without the consent of Mr. Jeffrey Prevey and Mr. Mark Frizzell or their replacements. No study which identifies you will be performed in the future without your written permission. If you agree to have the blood and urine stored, you can ask that the stored blood or urine be destroyed at any time by contacting Dr. Luke Naeher at 706-542-2454. Refusal to agree to this testing would in no way prevent you from being in the program.

Please Check One:

( ) 1. **I agree** to allow a portion of my blood and urine sample from this program to be stored for possible future testing as explained above.

OR

( ) 2. **I do not agree** to allow a portion of my blood and urine sample from this program to be stored for future testing. These samples should not be used for anything but this program, and the samples should be destroyed one year after this program is finished.

Print Name: ______________________________

Signature: ______________________________

Witness: ______________________________

Date: ______________________________

If you have questions, concerns or complaints, please contact one of the investigators:

Luke P. Naeher, PhD
706-542-2454

Allison Stock, Ph.D
404-498-1034

I understand that I am agreeing by my signature on this form to take part in this research project and understand that I will receive a signed copy of this consent form for my records.

____
Signature of Investigator Date

____
Signature of Participant Date

Additional questions or problems regarding your rights as a research participant should be addressed to Chris A. Joseph, Ph.D. Human Subjects Office, University of Georgia, 606A Boyd Graduate Studies Research Center, Athens, Georgia 30602-7411, USA; Telephone (706) 542-3199; E-Mail Address IRB@uga.edu

<u>Consent Form #3: Occupational woodsmoke exposure and respiratory effects among wildland firefighters working at prescribed burns, Savannah River Site, SC, 2011</u>

I, ______________________________ agree to take part in the research study titled " **Development and validation of a woodsmoke biomarker in urine** " conducted by Dr. Luke Naeher from the Department of Environmental Health Science at the University of Georgia, USA [706-542-4104]. I understand that I do not have to take part if I do not want to. I can refuse to participate or stop taking part without giving any reason, and without penalty or loss of benefits. I can ask to have all of the information about me returned to me, removed from the research records, or destroyed.

The reason for this study is to obtain information on my exposure to air pollution from prescribed forest burns in southeastern US forests and to test a respiratory protection mask.

If I volunteer to take part in this study, I will be asked to do the following things:

1) Answer questions about my personal and work activities that might affect my exposure to air pollution and other chemicals in the environment. I can skip any questions that I do not feel comfortable responding to.
2) Wear personal air sampling equipment for 8-12 hours each work day for 12 sampling days.
3) Collect one pre-shift and one post-shift urine sample per workshift for 12 sampling days. The urine will be collected for analysis of woodsmoke related biomarkers of exposure and effect.
4) I will be given a list of specific foods that may contain chemicals that are present in woodsmoke. During the study I will be asked to avoid eating these foods, because the may interfere with the measurements which the researcher will be making on my urine samples. I will also be asked not to eat food cooked over an open fire.
5) Collect one pre-shift and post-shift finger stick blood sample per workshift for 12 sampling days. The blood will be collected for analysis of woodsmoke related biomarkers of effect.

I will receive a UGA research study t-shirt or equivalent and a $25 restaurant gift certificate at the end of the study as compensation for being in this study.

In order to process the payment for my participation, the researchers need to collect my name and mailing address on a separate payment form. This completed form will be sent to the Department of Environmental Health Science business office and then to the UGA Business Office. The researcher has been informed that these offices will keep my information private, but may have to release my name and the amount of compensation paid to me to the IRS, if ever asked. The researchers connected with this study have gone to great lengths to protect my survey information and will keep this confidential in locked files. However, the researcher is not responsible once my name and mailing address leave his office for processing of my payment.

The benefits for my workplace and community are that the air pollution and respiratory protection mask data may help leaders in occupational and public health agencies reduce elevated occupational and environmental exposures to me and others in my workplace and community.

Potential risks or discomforts include: The risks of drawing blood from a finger stick include discomfort at the site of the stick; possible redness; rarely an infection; and, uncommonly faintness from the procedure. This risk will be minimized by the use of standard sterile techniques as instructed by the researcher. The amount of blood taken should have no negative effects.

The blood will not be tested for HIV-AIDS. I understand that these urine and blood samples are not for diagnostic purposes**.**

Any information that is obtained in connection with this study and that can be identified with me will remain confidential and will be disclosed only with my permission or as required by law. I will be assigned an identifying number and this number will be used on all air monitoring and questionnaires I fill out. Some of the data and samples collected in this study will be shared without personal identifiers with colleagues at the University of California at Irvine, and at the University of Washington, Seattle.

The investigator will answer any further questions about the research, now or during the course of the project (706-542-2454).

I understand that I am agreeing by my signature on this form to take part in this research project and understand that I will receive a signed copy of this consent form for my records.

______________________________ ____

Signature of Investigator Date Signature of Participant
Date

Additional questions or problems regarding your rights as a research participant should be addressed to IRB Chairperson Institutional Review Board, University of Georgia, 629 Boyd Graduate Studies Research Center, Athens, Georgia 30602-7411, USA; Telephone (706) 542-3199; E-Mail Address IRB@uga.edu

APPENDIX B: BASELINE HEALTH QUESTIONNAIRE

Savannah River Site Fire Crew Health Questionnaire

Subject ID #: ___________________

Technician: ___________________________ Date: ___________________________

1. What is your age? _________
2. How many times a week do you do cardiovascular exercise for greater than 15 min? __________
3. How many years have you been a firefighter? ______________
4. How many years have you been working prescribed burns? ________________
5. Approximately how many prescribed burns have you worked in your career? ____________
6. How many work days a year would you estimate that you are exposed to smoke from a fire at work?
   0-10 11-30 31-50 51-100 101-150 151-200 >200
7. Do you wear any personal protective equipment (PPE) when fighting fires?................Y N
   - If yes, what type of PPE do you use and under what conditions do you use it?
   ____
8. Have you ever worn any personal protective equipment (PPE) when fighting fires?.....Y N
   - If yes, what type of PPE have you used and under what conditions did you use it?
   ____
9. Before working at this job have you had any respiratory problems?.............................Y N
10. Currently, do you have any respiratory problems?..Y N
    - If yes, please explain: _____________________________________
11. Have you ever used a bronchodilator or a puffer? .... Y N
    - If yes, do you currently use one:…………………………………………………..Y N
12. Do you usually cough first thing in the morning?..Y N
13. Do you usually cough at other times during the day or night?......................................Y N
14. Has your chest ever sounded wheezy or whistling when you have had a cold?............Y N
15. Has your chest ever sounded wheezy or whistling when you have not had a cold?.......Y N
16. Have you ever had episodes of shortness of breath?..Y N
17. Do you suffer from elevated blood pressure?...Y N
18. Do you have asthma?...Y N
19. Do you have allergies?...Y N
    - If yes, please describe type of allergy and symtoms________________________________
20. Have you ever done a spirometry test before?..Y N
    - If yes, did you have any problems?...Y N
    - If problems, please explain: _______________________________________
21. Does your biological father or mother have any of the following health problems:
    - chronic bronchitis…………………………………………………………………Y N
    - emphysema………………………………………………………………………..Y N
    - chronic obstructive lung disease…………………………………………………..Y N
    - asthma……………………………………………………………………………..Y N
    - lung cancer………………………………………………………………………...Y N

22. Have you ever had thoracic surgery? …………………………………………………Y N
23. Are you pregnant? ……………………………………………………………….. Y N
24. Have you ever smoked? ……………………………………………………….. Y N
    - If yes, how many years did you smoke? ________________
25. Do you currently smoke cigarettes? ……………………………………………….. Y N
    - If yes, how many cigarettes do you smoke a day? ________________
26. Do you currently smoke pipes or cigars? ………………………………………….. Y N
    - If yes, how many pipes or cigars do you smoke a day? ________________
27. Does anyone smoke cigarettes within your home on a regular basis? ………………...Y N
    - If yes, how many cigarettes does that person smoke a day? ________________
28. What kind of heating does your home have? (check all that apply)

☐ District Heating
☐ Central Healting (inside your building)
☐ Single Stoves/ Heaters
  ☐with electricity
  ☐with gas
  ☐with wood
  ☐with kerosene/paraffin
  ☐with fuel/heating oil
☐ Fireplace
☐ There is no heating
☐ Other: __________________

27. Does your home have? – (check all that apply)

☐ Air Conditioning
☐ A humidifier (include any humidifier built into your heating system or air conditioning)
☐ An electric air cleaner, ionizer, or air filter
☐ None of the above

APPENDIX C: DAILY QUESTIONNAIRE

Daily Activity Smoke Exposure Log

ID Number:___________________________
Date:_________________________________
Time of start of shift: ___________________
Time of end of shift**:** ___________________
Time of questionaire: ___________________

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1. Was there a prescribed fire today? YES NO

2. Did you assist in the prescribed fire? YES NO

If yes,

Which Compartment did you burn? ______

Approximately how many acres were burned? ______

3. Did you use any sort of respiratory protection today? YES NO

   If Yes, what type? __________________

4. Did you smoke any cigarettes/cigars during the work day? YES NO

   If Yes, how many? _________________

5. Were you around people who were smoking tobacco today? YES NO

   If Yes, how long? __________________

6. How much wood smoke would you feel that you encountered today?

None to very little low level medium level medium to high level high level

7. Did you notice or have any problems with the sampling equipment today?YES NO

   If yes, please explain (hose disconnection, early shut off, cyclone fell off, battery disconnected, etc.)

____
____
____
____

8. Have you been exposed to woodsmoke outside of work within the last 24 hours?

   If Yes, how long? __________________

9. Did you experience exposure to any of the following? Please circle the one that is applicable

Chain saw Dust Vehicle exhaust

10. What task were you doing when you were exposed to the item circled in No. 9?

____

APPENDIX D: TIME ACTIVITY DIARY

Time Activity Diary

Date _______________ ID Number ________________
Technician ___________________________

	Job Task																
Time	**Holding**						**Direct_ Attack**	**Lighting**				**Mop-Up**					
	Onfoot	Mule	4-wheeler	Vehicle	Dozer	Other		DrIptorch	ATV	Fusee	Other	Onfoot	Mule	4-wheeler	Vehicle	Dozer	Other
7:15																	
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