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Fire environment effects on particulate matter emission factors in southeastern U.S. pine-grasslands

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HIGHLIGHTS

- We tested fire environment effects on particulate matter emission factors ($EF_{PM2.5}$).
- 41 prescribed burns were measured in pine-grasslands of Florida and Georgia, USA.
- $EF_{PM2.5}$ increased from winter to summer and with pine needle content.
- $EF_{PM2.5}$ decreased with grass content and frequency of burning.
- Timber thinning and frequent prescribed burning should reduce $EF_{PM2.5}$.

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ABSTRACT

Particulate matter (PM) emission factors (EF_{PM}), which predict particulate emissions per biomass consumed, have a strong influence on event-based and regional PM emission estimates and inventories. PM < 2.5 μm aerodynamic diameter ($PM_{2.5}$), regulated for its impacts to human health and visibility, is of special concern. Although wildland fires vary widely in their fuel conditions, meteorology, and fire behavior which might influence combustion reactions, the $EF_{PM2.5}$ component of emission estimates is typically a constant for the region or general fuel type being assessed. The goal of this study was to use structural equation modeling (SEM) to identify and measure effects of fire environment variables on $EF_{PM2.5}$ in U.S. pine-grasslands, which contribute disproportionately to total U.S. $PM_{2.5}$ emissions. A hypothetical model was developed from past literature and tested using 41 prescribed burns in northern Florida and southern Georgia, USA with varying years since previous fire, season of burn, and fire direction of spread. Measurements focused on $EF_{PM2.5}$ from flaming combustion, although a subset of data considered MCE and smoldering combustion. The final SEM after adjustment showed $EF_{PM2.5}$ to be higher in burns conducted at higher ambient temperatures, corresponding to later dates during the period from winter to summer and increases in live herbaceous vegetation and ambient humidity, but not total fine fuel moisture content. Percentage of fine fuel composed of pine needles had the strongest positive effect on $EF_{PM2.5}$, suggesting that pine timber stand volume may significantly influence $PM_{2.5}$ emissions. Also, percentage of fine fuel composed of grass showed a negative effect on $EF_{PM2.5}$, consistent with past studies. Results of the study suggest that timber thinning and frequent prescribed fire minimize $EF_{PM2.5}$ and total $PM_{2.5}$ emissions on a per burn basis, and that further development of PM emission models should consider adjusting $EF_{PM2.5}$ as a function of common land use variables, including pine timber stocking, surface vegetation composition, fire frequency, and season of burn.

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1. Introduction

Particulate matter (PM) emission factors (EF_{PM}), typically expressed as the mass of PM emitted per mass of fuel consumed (g kg^{-1}), are essential for estimating regional and event-based atmospheric emissions from wildland fires. Emission of PM < 2.5 μm

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aerodynamic diameter ($PM_{2.5}$) is of particular concern because of its effects on human health (Naeher et al., 2007), reduction of visibility, radiative forcing (Reid et al., 2005a), formation of secondary pollutants (Koppmann et al., 2005), and role as condensation nuclei (Reid et al., 2005b). For these reasons it is regulated by the U.S. Environmental Protection Agency (EPA). Calculation of regional $PM_{2.5}$ emissions from wildland fires typically involves multiplication of the estimated burned area, estimated fuel consumption per unit area, and $EF_{PM2.5}$, followed by model-based predictions of $PM_{2.5}$ dispersion, longevity, and deposition (Battye and Battye, 2002). Although wildland fires vary widely in their fuel conditions, meteorology, and fire behavior, the $EF_{PM2.5}$ component of this equation is typically a constant for the region being assessed (Andreae and Merlet, 2001) or the general fuel or vegetation type burned (van der Werf et al., 2010; Akagi et al., 2011; Urbanski et al., 2011), although it additionally may be weighted by estimated contributions from flaming versus smoldering phases of combustion (Prichard et al., 2007; Hardy et al., 2010; Lutes, 2013). These approaches depend on the assumption that the applied $EF_{PM2.5}$ is acceptably robust over a wide range of geographic, climatic, and local environmental conditions.

Evidence suggests that certain local fuel and environmental conditions affect $EF_{PM2.5}$ through their influence on combustion processes. Such processes are often described in terms of combustion efficiency (CE), the proportion of carbon (C) released as CO_2 relative to C in all other emissions, which is inversely related to $EF_{PM2.5}$ (Janhäll et al., 2010) and often used to calculate $EF_{PM2.5}$ indirectly. Fuel moisture tends to decrease CE and increase $EF_{PM2.5}$ because it absorbs energy that would otherwise be available for combustion, and emitted water vapor dilutes volatized gases and reduces the rate of oxidation reactions (Ward et al., 1989). Increasing fuel moisture tends to shift the emission source from flaming to smoldering combustion, the later having a much lower CE and higher $EF_{PM2.5}$ (Hardy et al., 2010). Variation in fuel moisture, reflecting proportion of live fuel and response of dead fuel to ambient conditions, has been attributed to seasonal differences in $EF_{PM2.5}$ in tropical savanna fires (Hao et al., 1996; Scholes et al., 1996; Ward et al., 1996; Hoffa et al., 1999; Korontzi et al., 2003). Research on gasoline combustion engines has shown higher ambient temperature of intake air to decrease PM emissions relative to energy released (Nam et al., 2008) and higher humidity to increase emissions (McCormick et al., 1997; Rahai et al., 2011), although such direct effects of ambient air conditions on wildland fire $EF_{PM2.5}$ has not been studied. $EF_{PM2.5}$ also responds to oxygen availability (Hegg et al., 1990), which is influenced by fuel particle size and bulk density (packing ratio) (Ward et al., 1980, 1983).

Fire behavior, reflecting fuel, weather, and topography as well as direction of fire spread relative to the wind, might also influence $EF_{PM2.5}$. Field experiments have suggested that $EF_{PM2.5}$ decreases with increasing reaction intensity (RI, rate of heat released per unit area) in prescribed burns because of stronger heat feedback and convection resulting in higher CE (Sandberg, 1974; Ward and Hardy, 1984). Results for fireline intensity (FI, rate of heat release per length of fire line) suggest that $EF_{PM2.5}$ initially decreases with increasing FI but above some level begins to increase due to oxygen deficiency as the depth of the flaming zone increases (Ward et al., 1980, 1983; Ward and Hardy, 1991). FI is typically an order of magnitude higher for fires running with the wind (head fire) than those spreading against the wind (backing fire) (Hmielowski, 2013), such that location on the fire perimeter or prescribed fire ignition pattern might influence $EF_{PM2.5}$.

Wildland fire $EF_{PM2.5}$ might also be influenced by ecological characteristics of the area burned, including plant community type and changes in fuel characteristics during post-fire succession. $EF_{PM2.5}$ has been shown to vary among general plant community types, such as forest, savannas, grasslands, and brushlands (Urbanski et al., 2009; Janhäll et al., 2010), attributable to variation in physical and chemical characteristics of the fuel matrix reflecting the proportions of shrub, grass, and litter fuels (Ward et al., 1996). Grass dominance is generally associated with low $EF_{PM2.5}$ because it tends to burn readily through flaming combustion (Ward et al., 1996; Urbanski et al., 2009; Janhäll et al., 2010). Pine needle litter has been found to have a disproportionately high $EF_{PM2.5}$ (Sandberg, 1974) despite its high flammability and energy content (Reid and Robertson, 2012). In most community types, time since previous fire corresponds to an increase in total fine fuel, woody plant dominance, leaf litter, and duff and a decrease in grass, forbs, and percentage of live fuel (Binkley et al., 1992; Peterson et al., 2007; Reid et al., 2012). These changes correspond to an overall decrease in fuel energy content (Hough, 1969; Reid and Robertson, 2012) and increase in fuel bulk density, which might promote higher $EF_{PM2.5}$ (Ward and Hardy, 1991). However, these changes also correspond to a reduction in the percentage of live fuel, making it difficult to predict the net effect of time since fire on $EF_{PM2.5}$.

To the degree that such factors predict $EF_{PM2.5}$, there is an opportunity to improve $PM_{2.5}$ emission models by considering their effects. The goal of this study was to identify which if any commonly measured fuel, fire, and weather variables during prescribed fires in southeastern U.S. pine-grasslands influences $EF_{PM2.5}$ to provide a theoretical foundation for further empirical model development. Estimates of $PM_{2.5}$ emissions are especially important in this region because of its frequent prescribed burning and wildfire and resulting disproportionate contribution to the nation's annual $PM_{2.5}$ emissions (Aurell and Gullett, 2013) and non-attainment of EPA standards for $PM_{2.5}$ in certain urban areas within the region (EPA, 2014). The study was designed to incorporate the range of variables most commonly considered by prescribed fire managers in planning burns: time since last fire, season of burn, ignition pattern (head versus backing fire), ambient air conditions, and fuel composition. Our approach was to measure these and associated environmental variables and $EF_{PM2.5}$ during burns under a wide range of fire conditions, then assess the relative effects of these variables on $EF_{PM2.5}$ using Structural Equation Modeling (SEM). The SEM analyses focused on fire behavior dominated by the flaming phase of combustion with an emphasis on comparing effects of environmental variables rather than estimating total emissions or event-based (all phases combined) emission factors, although smoldering-dominated combustion and MCE were measured for a subset of burns and reported for purposes of discussion.

2. Materials and methods

2.1. Fire environment measurements

Field work was conducted on the 1619-ha Tall Timbers Research Station and Land Conservancy (30°40′N, 8°14′W) and the 1222-ha Pebble Hill Plantation (PHP) (30°46′N, 84°3′W) between Tallahassee, Florida, and Thomasville, Georgia, USA. The communities studied were open-canopy pine-grasslands with either native (never plowed) or old-field (post-agriculture) surface vegetation (Ostertag and Robertson, 2007). They have been managed with single tree selection forestry and prescribed fire applied at mostly 1–2 year intervals since European settlement or abandonment of agriculture in the early 20th century (Reid et al., 2012), although certain burn units were recently fire-excluded up to four years for purposes of this and other studies.

Prescribed burns were applied in 2010, 2011, and 2012 on dates ranging from January to August to include the period when burns are typically applied in the region and include fires in the dormant

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