Particulate Matter Emission Factors in Southeastern U.S. Pine-grasslands

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C<sub>x</sub>H<sub>y</sub>O<sub>z</sub> + 2O<sub>2</sub> → H<sub>2</sub>O, CO<sub>2</sub>, CO, PM, NO, NO<sub>2</sub>, VOCs (CH<sub>4</sub>, PAHs)
PM$_{2.5}$ Emission Factor (EF) = PM$_{2.5}$ emitted / fuel consumed
Emissions Inventories

- Burned Area
- Fuel Loading
- Fuel Consumption
- Emission Factor
- Emission Production Rate
- Dispersion/Concentration
Factors potentially influencing $E_{PM2.5}$

- Combustion phase (flaming, smoldering, glowing)
- Combustion efficiency ($CO_2$/ total C released)
- Fuel moisture
- Fuel bulk density (packing ratio)
- Fuel composition
- Fire behavior

- Community type
- Season
- Weather
- Time since fire
Chaparral
Grass
Pocosin, palmetto
Conifer forest

Rx fires

MCE

0.86
0.88
0.90
0.92
0.94
0.96

wildfires

southeast
Mountain west

Urbanski et al. 2012
Purpose

- Investigate effects of fire environmental conditions and ecological variables on PM$_{2.5}$ emission factors within southeastern U.S. pine-grassland communities
- Suggest whether or not developing models to predict PM$_{2.5}$ emissions using such conditions as input would improve emissions estimates
Methods

- Measure a $\text{EF}_{\text{PM2.5}}$ in the field from the ground during prescribed burns across a range of common environmental conditions.

- Use Structural Equation Modeling to identify variables influencing $\text{EF}_{\text{PM2.5}}$ and their interactions.
Fire Environmental Variables:

Fuel load, moisture, and consumption

- Live herbaceous
- Aerated 1-hr (0-0.6 cm dead grass, pine needles, etc.)
- Fine 1-hr unaerated (smaller particles)
- 10-hr (0.6-2.5 cm)
- Bed depth and density
- Time since fire
Fire Environmental Variables:

**Fire behavior**

- Heat per unit area (kJ m$^{-2}$)
- Reaction Intensity (kJ m$^{-2}$ s$^{-1}$)
- Fireline Intensity (kJ m$^{-1}$ s$^{-1}$)
- Flaming and smoldering residence time
- Maximum temperature
- Flame length
- Rate of spread
- Ignition type (backing, heading)
Fire Environmental Variables:

Weather

- Relative humidity
- Ambient temperature
- Wind speed
- Keetch-Byrum Drought Index
- Season
Tall Timbers Fire Ecology (Stoddard) Plots

1 Year Interval

2 Year Interval

3 Year Interval
Pebble Hill Fire Plots, Thomasville, Georgia

4 months post-burn

1 year post-burn

3 years post-burn

4 years post-burn
Pebble Hill Fire Plots, Thomasville, Georgia

September 2009

February 2010
Emission factors

\[ EF_{PM} = \frac{PM\text{ emitted (g)}}{Fuel\text{ consumed (kg)}} \]

\[ EF_{PM} = \frac{PM_{\text{plume}} - PM_{\text{ambient}}}{C_{\text{plume}} - C_{\text{ambient}}} \times W \]
PM, CO₂, CO sample

Emission intake
Principal Component Analysis (PCA) – Reduce variables
Structural Equation Model (SEM) – Theoretical model
Structural Equation Model (SEM) – Initial model
Structural Equation Model (SEM) – Final model

% GRASS

-0.39 (-11.2)

-0.32 (-0.27)

0.04 (0.15)

% NEEDLES

0.46 (0.46)

TP

0.29 (0.46)

0.08 (-5.35)

EF

r² = 0.40

χ² = 1.64

3 df

P = 0.651
8.4 m² ha⁻¹ (36 ft²/acre)
15% needles
$\text{EF}_{PM2.5} = 15.4 \text{ g kg}^{-1}$

18 m² ha⁻¹ (78 ft² ac⁻¹)
29% needles
$\text{EF}_{PM2.5} = 24.1 \text{ g kg}^{-1}$
TP = 33 C (91 F)
RH = 47
VD = 15
EF$_{PM2.5}$ = 24.3 g kg$^{-1}$

TP = 20 C (68 F)
RH = 38
VD = 7.0
EF$_{PM2.5}$ = 18.8 g kg$^{-1}$
Conclusions

• Fuel characteristics have significant effects on $\text{EF}_{\text{PM2.5}}$ in periodically burned southern pine-grasslands
• Lowest $\text{EF}_{\text{PM2.5}}$ was associated with low pine stocking, high grass loads, frequent burning, and dormant season burns
• Model development for predicting $\text{EF}_{\text{PM2.5}}$ based on forest structure and fuel composition should improve the accuracy of PM emission estimates
• Low $\text{EF}_{\text{PM2.5}}$ conditions generally correspond with goals for ecological management of this community type, apart from dormant season burning
• Effect of season on $\text{EF}_{\text{PM2.5}}$ appears to be because of air moisture rather than fuel moisture
• Growing season burns promote grass cover over time which might offset higher $\text{EF}_{\text{PM2.5}}$
Emission factors

Mass balance method

\[ EF_{PM} = \frac{PM_{\text{plume}} - PM_{\text{ambient}}}{C_{PM} + C_{\text{plume}} - C_{\text{ambient}}} \times W \]

Carbon isotope method

\[ EF_{PM} = \frac{PM_{\text{plume}} - PM_{\text{ambient}}}{C_{PM} + C_{\text{plume}} \left( \frac{d13C_{\text{plume}} - d13C_{\text{ambient}}}{d13C_{\text{fuel}} - d13C_{\text{ambient}}} \right)} \times W \]
The graph shows a linear relationship between EF-PM_{2.5} (g/kg, CACC assumption) and EF-PM_{2.5} (g/kg, δ^{13}C method). The equation of the line is $y = 0.85x + 4.53$, with a correlation coefficient $r^2 = 0.93$. The slope of the line is significantly different from unity, indicating a slight deviation from a 1:1 ratio.
Emission factor assumption:
$PM_{\text{plume}}$ and $CO_{2\text{plume}}$ are evenly mixed
Emission factor assumption: $PM_{\text{plume}}$ and $CO_{2\text{plume}}$ are evenly mixed
$\text{PM}_{2.5} \text{ conc (mg m}^{-3}\text{)}$  |  Fire-$\text{CO}_2$ (ppm)  |  MCE  |  $\text{EF}_{\text{PM2.5}}$ (g kg$^{-1}$)
---|---|---|---
1.4  | 255  | 0.94  | 5.3
3.1  | 56   | 0.94  | 46.4
Conclusions

- Ambient CO$_2$ concentrations are increased in the fire plume relative to ambient air conditions.
- There is a non-stoichiometric relationship between ambient CO$_2$ + O$_2$ and gaseous products of combustion that results in a systematic 15% ($\pm$2%) under-estimation of EF$_{PM2.5}$ using the traditional mass balance method.
- The assumption that emitted PM$_{2.5}$ and CO$_2$ are well mixed holds true only within flaming combustion convection column.
- Conversely, emitted PM$_{2.5}$ and CO$_2$ are rapidly decoupled (<1 hr) where convective mixing is weak.
- Such conditions might include the turbulent edges and exterior of convection columns and convection from low-energy combustion (low intensity flaming or smoldering combustion).
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