Health Effects of Wildfire Emissions

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All microscope images from current CDPH/EHL research, unless cited otherwise.
Disclaimer

This presentation is intended to provide scientific background information on wildfire smoke and ash measurement; it does not represent direct guidance for the public or responders.
Presentation outline

1. Introduction

2. Wildfire PM
   a. Wildfire particulate matter (PM) health effects
   b. Smoke PM
   c. Cleanup / post-fire PM
   d. Effect of particle size on inhalability and transport

3. Wildfire gases

4. Conclusions
Introduction

• Wildfires produce incomplete combustion chemicals in the form of particles and gases

• Particle and gas sources during wildfire:
  • Burning forest / biomass
  • Burning residences and vehicles
  • Burning commercial/industrial properties and supplies

• Particle sources after wildfire, during cleanup:
  • Residues from all of the above
  • Burned and unburned building materials exposed by fire damage
Wildfire PM Health Effects

• **Wildland firefighters** present respiratory and neurological symptoms after fires, as well as longer-term decrements in lung function (Austin, 2008; Domitrovich et al, 2017)

• **Acute exposure of general public** to wildfire smoke associated with increased hospital admissions for respiratory, cardiovascular, and cerebrovascular events (Wettstein et al, 2018)

• **Need for more research on chronic exposure to wildland fire smoke exposure** (Domitrovich et al, 2017)
General PM health effects

- Inhalation of all PM beyond critical levels and durations can cause acute and chronic inflammation, as well as respiratory and cardiopulmonary health effects.

- Numerous epidemiology studies have shown $\text{PM}_{2.5}$ and $\text{PM}_{10-2.5}$ (coarse PM) associated with increased mortality, hospitalization, and asthma emergency room visits, especially for children and susceptible individuals (Pope and Dockery, 2006; Peters et al, 2011; Lee et al, 2006; Adar, 2014)

- Public $\text{PM}_{2.5}$ and $\text{PM}_{10}$ regulations and guidelines based on exposure/disease findings of major PM health studies:
  - Chronic/long term average (annual)
  - Daily average (24-hr)

- Shorter term exposure/disease studies and guidelines currently more limited, need more research:
  - Occupational (Cal/OSHA) regulations = 8-hour “nuisance dust” limits ~ 1,000x greater than public health limits
  - 60 min $\text{PM}_{2.5}$ exposures associated with increased cardiac arrhythmia (He et al, 2011)
Major wildfire particle type #1: Organic carbon

- Amorphous, organic carbon (OC) particles and spherical “tar balls”, 50-500 nm
  (Adachi and Buseck 2011; Posfai et al., 2003; China et al 2013; Hand et al., 2005; Wagner et al, 2012)
  - Dominant PM type in low temperature, smoldering biomass emissions
  - wildfires, low-temperature cookstoves, and crop burning
  - Water soluble, enriched in potassium and sulfur

- Ultrafine PM from peat wildfires causes significantly decreased cardiac function
  (Kim et al 2014)
Major wildfire particle type #1: Organic carbon

- OC = alkanes, alkenes, alkanols, carboxylic acids, phenols, levoglucosan, diterpenoids, and ~5% polycyclic aromatic hydrocarbons (PAH) \( (\text{Robinson et al, 2011}) \)

- Wildfire and prescribed burn-measured PAHs include several known or probable carcinogens and toxics [e.g., Benzo [a] pyrene, Benzo (b + k) fluoranthene] \( (\text{CARB, 2003; Robinson et al, 2011}) \)
  
  - High temperature (flaming) burns produced 3x higher PAH levels, including prominent Benz[a]anthracene and chrysene + triphenylene
Major wildfire particle type #2: Soot

- Relatively minor component of biomass fires (5-10%)
- Major component of burned diesel (S), unleaded and leaded gasoline (Pb and Br), and burning tires

(China et al., 2013; Adachi and Buseck, 2011)
Major wildfire particle type #2: Soot

- Health effects associated specifically with soot particles, above and beyond general PM
  - Correlation of short term health effects stronger with diesel “black carbon” than with general PM (Schwartz et al, 2005; Grahame, 2009)
  - Diesel soot toxicity theorized to be influenced by PAH coating (Steiner et al, 2016)
- Short term soot exposure (5 min – 24 hr) associated with increased heart rate variability (Adar et al, 2007)
Major wildfire particle type #3: Ash

- Remnants of burned plants and building materials, mostly > 2.5 um on a mass basis
  - Plant ash: C, K, Cl, Ca, Si, S, and Na (Kurkela et al, 1997; Li et al, 2004; Wagner et al 2012; Biolex, 2009; Pitman, 2006)

- Inhalation of PM$_{10-2.5}$ causes inflammation; can contain metals, especially if emitted from fires in urban areas (Adar et al, 2014)
Major wildfire particle type #3: Ash

- Metals in soil and ash from 2007-9 CA wildfires (Wolf et al, 2010)
  - elevated levels of chromium(VI) [toxic, carcinogenic]
  - elevated levels of arsenic, lead, and antimony
  - highly caustic (pH = 10-12)

- Fly ash = spherical, inorganic PM from high temperature biomass burning, or coal (Lind et al, 2000)
Other wildfire particle type: petroleum and plastic emissions

- **Burning oil**: PM\textsubscript{10-2.5} or larger OC (Miller and Linak, 1996; Huffman et al., 2000; Lighty et al., 2000; Marrone et al. 1983; Allouis et al. 2003; Lippman et al., 2006)
  - Coke particles with vanadium and nickel (and Zn and Fe)
  - PM\textsubscript{10} containing Ni (and possibly V) causes increased heart rate variability above that caused by normal PM\textsubscript{10}

- **Burning synthetic materials** produced >10x more PM\textsubscript{2.5} than wood; mostly UFP <150 nm (Fabian et al. 2010)
  - **styrene** (e.g. disposable plastic glasses and dishes, insulation, appliances, electronics, toys, tires, vehicles)
  - **vinyl** polymers (e.g. PVC pipe, wiring, siding, resin chairs and tables)
  - **Arsenic** (sometimes >STEL), cobalt, chromium, lead, phosphorous, mercury, and PAHs.
  - Wood product PM increased with fraction of adhesives

Wagner et al., 2003
Cleanup / post-fire PM

- Ash and exposed building materials are potential sources of carcinogens and toxics
  - Carcinogenic asbestos
  - Irritant fiberglass dust
  - Toxic metals (lead, chromium, arsenic, copper, mercury) from partially burned batteries, paint, electronics, solder, pipes, treated wood

(Redding Record Searchlight, August 2018)
Airborne particulate matter from structure fires

- Fully encapsulated additives pose low risk, but burned materials may become friable (can crumble and release particles)

- Asbestos released by heat, formerly encapsulated in brakes (De Vita et al., 2012)

- Crumbled paint with micrometer sized lead (bright spots) (Wall et al., 2002)

- Crumbled furniture foam with brominated flame retardant (Wagner et al., 2013)
Exposed building material particle types – non Asbestos

- Difficult for visual inspection to distinguish non-hazardous fibrous materials from asbestos
  - need analysis by accredited asbestos laboratory to know with certainty
Effect of Particle size on inhalability

Ash = PM$_{10-2.5}$ more likely to deposit in nose and throat

Soot, tar balls = PM$_{2.5}$ more likely to deposit in lungs & trachea
Effect of Particle size on transport

Ash = PM_{10-2.5} will settle to ground at higher rate

Most ash is >>2.5 um, so won’t be reflected in PM_{2.5} AQI measurements

Soot, tar balls = PM_{2.5} plume more likely to stay aloft

However, in some cases, shifting meteorology can also force entire PM_{2.5} plume to the ground and into breathing zone

Hinds, 1982

Harnly et al, 2012
Wildfire PM Measurement – for all, need to consider effective measured particle size

<table>
<thead>
<tr>
<th>PM measurement type</th>
<th>Measured quantity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Samplers (need to take back to lab to analyze)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filters or impactors</td>
<td>Gravimetric mass</td>
<td>True mass; size fractions</td>
</tr>
<tr>
<td>Grids on impactor or thermophoretic samplers</td>
<td>Single particle SEM/EDS or TEM/EDS -&gt; count and 2D physical size, estimated mass</td>
<td>Detailed single particle characterization; size distributions</td>
</tr>
<tr>
<td>Passive PM samplers *</td>
<td>Single particle SEM/EDS or TEM/EDS -&gt; count and 2D physical size, estimated mass</td>
<td>Low cost; longer sampling times; detailed single particle characterization; size distributions</td>
</tr>
<tr>
<td><strong>Continuous monitors (best time resolution)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photometers</td>
<td>Light scattering -&gt; correlated with mass</td>
<td>Sensitive to particle size and composition</td>
</tr>
<tr>
<td>Passive optical sensors *</td>
<td>Light scattering -&gt; correlated with mass</td>
<td>Low cost; very sensitive to particle size and composition</td>
</tr>
<tr>
<td>Beta attenuation</td>
<td>Beta radiation absorption -&gt; correlated with mass</td>
<td></td>
</tr>
<tr>
<td>Aethalometers</td>
<td>Light absorption at specific wavelengths -&gt; correlated with black carbon or brown carbon mass</td>
<td></td>
</tr>
<tr>
<td>Optical particle counters, condensation counters, and scanning electrodynamic or aerodynamic classifiers</td>
<td>Single particle light scattering (electrical or aerodynamic mobility) -&gt; count, estimated mass</td>
<td>Size distributions</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satellite/remote sensing *</td>
<td>Light scattering -&gt; correlated with mass, or qualitative smoke density</td>
<td>Does not require sampler/site visits; limited temporal and spatial resolution</td>
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</tbody>
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* Good candidates for improved spatial resolution measurements
Wildfire Gas Emissions by Mass  (Urbanski et al, 2009)

• **Complete** combustion products
  
  • $\text{CO}_2 = \sim 93\%$ of measured smoke mass

• **Incomplete** combustion products
  
  • Major mass components (total $\sim 6\%$):
    
    • $\text{CO} > 5\%$
    
    • $[\text{PM}_{2.5} \sim 1\% ]$
    
    • $\text{CH}_4 \sim 0.2\%$

  • Other components (total $\sim 1\%$):
    
    • Non-methane volatile organic compounds (VOCs)
      
      • alkanes, alkenes, aromatics, and oxygenated compounds (aldehydes, ketones, alcohols, furans, acids)
    
    • Nitrogen (and sulfur) oxides
Hazardous Components of Wildfire Gas Emissions

• Wildfire smoke gas hazard types (adapted from Fabian et al, 2010)

<table>
<thead>
<tr>
<th>Type of gas-phase hazard</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphyxiants</td>
<td>CO, CO₂, H₂S</td>
</tr>
<tr>
<td>Irritants and allergens</td>
<td>NH₃, HCl, NOₓ, phenol, SO₂, isocyanates</td>
</tr>
<tr>
<td>Carcinogens</td>
<td>benzene, styrene, formaldehyde</td>
</tr>
</tbody>
</table>

• Gas chemical concern groups based on Hazard Ratios = EF / TLV (adapted from Austin, 2008):

<table>
<thead>
<tr>
<th>Hazard ratio groups</th>
<th>Gas emission species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>CO, formaldehyde, acrolein, NOₓ, [PM]</td>
</tr>
<tr>
<td>Group 2 (One order of magnitude less)</td>
<td>benzene, CO₂, [PAH], NH₃, furfural</td>
</tr>
<tr>
<td>Group 3 (Two orders of magnitude less)</td>
<td>acetaldehyde, 1,3-butadiene, methane, methanol, styrene, acetonitrile, propionaldehyde, toluene, methyl bromide, methyl ethyl ketone, acetone, methyl chloride, xylene, phenol, tetrahydrofuran, methyl iodide, mercury</td>
</tr>
</tbody>
</table>

• Hazardous gas emissions from associated burning products and building materials (Fabian et al, 2010)
  • Polystyrene plastics: benzene, phenols, and styrene
  • Vinyl compounds: acid gases (HCl and HCN) and benzene
  • Wood products: formaldehyde, formic acid, HCN, and phenols
  • Roofing materials: SO₂ and H₂S.
Wildfire Hazardous Gas Monitoring – potential tracers

- CO most often exceeded NIOSH IDLH, STEL, and OSHA TWA; correlated with formaldehyde, acrolein (Austin, 2008)

- Cerex UV spectrometer used to determine whether a single chemical compound could be used as marker for all (Tualatin Valley Fire & Rescue, 2011)
  - CO not correlated with NO₂, toluene, O₃ or aldehydes
  - Although no single best marker found, best pairwise correlations were:

<table>
<thead>
<tr>
<th>Gas-phase Species Pair</th>
<th>Correlation (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone – NO₂</td>
<td>0.966</td>
</tr>
<tr>
<td>total aldehydes – phenol</td>
<td>0.945</td>
</tr>
<tr>
<td>Toluene – Phenol</td>
<td>0.943</td>
</tr>
<tr>
<td>Toluene – glutaraldehyde</td>
<td>0.889</td>
</tr>
<tr>
<td>Toluene – Benzene</td>
<td>0.564</td>
</tr>
<tr>
<td>Styrene – Benzene</td>
<td>0.515 - 0.559</td>
</tr>
<tr>
<td>total aldehydes – benzene</td>
<td>0.51</td>
</tr>
</tbody>
</table>
Wildfire Gas Measurement (Tualatin Valley Fire & Rescue, 2011; Fabian et al, 2010; Urbanski et al, 2009)

- **Continuous monitors**
  - **Electrochemical sensors and colorimetric tubes**
    - some interference from other compounds
  - **Photo-ionization detectors**
    - Standard size lamp in multi-gas detectors proved ineffective; more powerful lamp recommended
  - **Long path UV spectrometers**
    - Interfering compounds with coincident wavelengths caused issues with toluene and styrene
  - **Portable GC-MS**
    - Detection limit sometimes too high for low level measurements
  - **OP-FTIR**
    - difficult to successfully implement in the field; too slow, insufficient signal-to-noise
- **Passive gas canisters and badges**
  - need to take back to lab to analyze (e.g., GC/MS)
Conclusions

- Inhalation of particulate matter (PM) can cause acute and chronic inflammation, cardiovascular health effects
  - Wildfire PM can contain additional carcinogens and toxic chemicals beyond general PM

- Wildfire $\text{PM}_{2.5}$ (fine PM) during and after fires
  - Organic carbon (PAHs) and soot from burned biomass and plastics; friable asbestos fibrils
  - more likely to deposit in deep lungs
  - more likely to remain high in overhead plume if meteorology is favorable

- Wildfire $\text{PM}_{10-2.5}$ (coarse PM) during and after fires
  - Ash and other friable building material additives (minerals, metals)
  - more likely to deposit in nose/throat
  - more likely to settle out from plume to ground
Conclusions

- **Gas phase** smoke compounds can cause asphyxiation, inflammation, cancer
  - Complex array of compounds at often low concentrations
  - Many species not routinely monitored
- Need for more wildfire studies
  - Health effects of <24 hr, <1 yr exposures
  - Spatial smoke and ash variability across regions
- PM and gas **measurement devices** continue to improve
  - Balance between low cost vs. accuracy, specificity