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Estimating mercury emissions resulting from wildfire in forests of the Western United States

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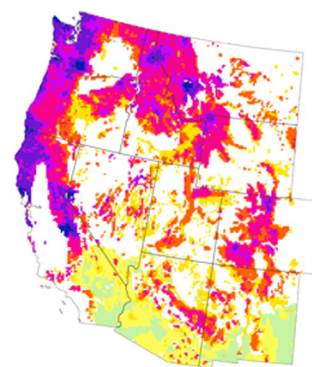
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HIGHLIGHTS

- Understanding Hg releases from fires is important for assessment of global releases.
- Release of Hg from Western US forest was estimated as a function of burn severity.
- Emission factors need to be carefully evaluated in modeling.
- Release is not proportional to biomass consumption, but tied to subsurface heating.
- Thus, areas subject to high-severity have greater Hg emission.

GRAPHICAL ABSTRACT



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ABSTRACT

Understanding the emissions of mercury (Hg) from wildfires is important for quantifying the global atmospheric Hg sources. Emissions of Hg from soils resulting from wildfires in the Western United States was estimated for the 2000 to 2013 period, and the potential emission of Hg from forest soils was assessed as a function of forest type and soil-heating. Wildfire released an annual average of 3100 ± 1900 kg-Hg y^{-1} for the years spanning 2000–2013 in the 11 states within the study area. This estimate is nearly 5-fold lower than previous estimates for the study region. Lower emission estimates are attributed to an inclusion of fire severity within burn perimeters. Within reported wildfire perimeters, the average distribution of low, moderate, and high severity burns was 52, 29, and 19% of the total area, respectively. Review of literature data suggests that that low severity burning does not result in soil heating, moderate severity fire results in shallow soil heating, and high severity fire results in relatively deep soil heating (<5 cm). Using this approach, emission factors for high severity burns ranged from 58 to 640 $\mu\text{g-Hg kg-fuel}^{-1}$. In contrast, low severity burns have emission factors that are estimated to be only 18–34 $\mu\text{g-Hg kg-fuel}^{-1}$. In this estimate, wildfire is predicted to release 1–30 g Hg ha^{-1} from Western United States forest soils while above ground fuels are projected to contribute an additional 0.9 to 7.8 g Hg ha^{-1} . Land cover types with low biomass (desert scrub) are projected to release less than 1 g Hg ha^{-1} . Following soil sources, fuel source contributions to total Hg emissions generally followed the order of duff > wood > foliage > litter > branches.

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1. Introduction

Transport and deposition of Hg from natural and anthropogenic sources has led to its enrichment in surficial soils throughout the geosphere (Driscoll et al., 2013). This pool of Hg can be transported into surface waters and sediments, and potentially be converted into methylmercury (MeHg), a potent neurotoxin that impairs global fisheries and poses risk to ecosystems and human health (Selin et al., 2007; Poulin and Gibb, 2008; Driscoll et al., 2013). One of the major sources of Hg to the global atmospheric pool is the mobilization of Hg during biomass burning (Friedli et al., 2009; Pirrone et al., 2010; Driscoll et al., 2013).

Forest soils are effective at sequestering atmospherically-deposited Hg. The sequestration of Hg has led to a 15–20% increase in the content of Hg in forest soils around the globe over the last century (Grigal, 2003; Selin, 2009; Driscoll et al., 2013). The transfer of Hg into forest soils occurs when gaseous Hg (Hg^0) is taken up, mainly by leaf stomata, and transferred to the forest floor through litterfall (St. Louis et al., 2001; Rea et al., 2000, 2001; Obrist, 2007; Rutter et al., 2011; Demers et al., 2013; Jiskra et al., 2015). Once at the ground surface, Hg is subsequently transferred to the soil column during degradation of litter materials (St. Louis et al., 2001; Rea et al., 2002; Obrist et al., 2011; Pokharel and Obrist, 2011). Hg that is transferred into the soil column is strongly correlated with soil organic matter (SOM; Grigal, 2003; Engle et al., 2006; Biswas et al., 2007; Obrist et al., 2011). The correlation between Hg and SOM is due to the formation of strong bonds between Hg and reduced organic sulfur moieties within the organic matter (Xia et al., 1999; Skyllberg et al., 2000, 2006). Temperate forests of the Western United States typically contain 40–300 g-Hg ha^{-1} , which is in the 0–40 cm of soil (>90%), the forest floor (litter and duff layers), and above-ground biomass (Obrist, 2012).

Wildfire has the potential to mobilize Hg from biomass, O-horizon soil (organic soil of litter and duff) and A-horizon soil (shallow mineral soils), but not from the C-horizon (deeper mineral soil) (Friedli et al., 2001, 2003; Engle et al., 2006; Wiedinmyer and Friedli, 2007; Obrist et al., 2007; Biswas et al., 2007, 2008; Burke et al., 2010; Woodruff and Cannon, 2010). During combustion, fuels release Hg primarily as Hg^0 , though fuel moisture can increase particulate Hg (PHg) emissions (Friedli et al., 2003; Obrist et al., 2007). Hg bound by the soil matrix begins to thermally desorb at 150 °C (Biester and Scholz, 1996) and soil Hg has been shown to be re-emitted during wildfire if sufficient soil heating takes place (Biswas et al., 2007, 2008; Woodruff and Cannon, 2010). The extent to which wildfire liberates Hg from each reservoir (canopy, fuel bed, soil) depends on the severity of burning (Biswas et al., 2007). The severity of burning is a product of the intensity and duration of the fire and depends on available fuel, ambient temperature, and relative humidity, canopy structure, forest health, wind speed, and many other potential factors (Parsons, 2003; Neary et al., 2005; Certini, 2005; Keeley, 2009). A low-severity fire may only minimally consume the canopy, have low flame height and burn scars, and result in minimal duff consumption leaving duff layers intact (Parsons, 2003; Neary et al., 2005; Certini, 2005; Keeley, 2009). High-severity burns can result in combustion of the entire litter load, a large portion of the organic horizon, and a large fraction of the crown foliage (Parsons, 2003; Neary et al., 2005; Certini, 2005; Keeley, 2009). In addition, the depth of soil heating is a function of fire severity at the soil surface. For instance, a low burn intensity fire coupled with a long duration, such as a smoldering log, may transfer more heat to soil than a high-intensity, short-duration event, such as a chaparral fire (Parsons, 2003). Heat is quickly dissipated below the soil surface due to the insulating properties of soil and the presence of soil moisture (Certini, 2005). A fire burning at 850 °C on the surface will generally not raise the subsurface temperature over 150 °C below 5 cm (Debano, 2000). Within the strong thermal gradient, it is likely that soil only reaches temperatures of 200–300 °C (Certini, 2005).

As part of the Western North American Mercury Synthesis (WNAMS) effort, the goal of this study was to synthesize data on Hg emissions resulting from wildfires, and analyze these data in the context of Hg distribution and fire occurrence within the 11 Western States including Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, Utah, Washington, and Wyoming. In the Western States, warming air-temperatures and extended droughts have led to increasing occurrence and severity of wildfire (Westerling et al., 2006; Littell et al., 2009; Westerling et al., 2014). Additionally, the practice of fire exclusion from the early 1900s on has increased fuel-loading, altering fire behavior in some areas (Miller et al., 2009). Large-scale wildfire disturbance in forests of the Western States will likely lead to greater release of Hg, especially if forests with long fire recurrence intervals begin burning at increased rates. Within the Western States, forest types, fuels, and fire behaviors can vary across ecotypes; however, there is currently no assessment of how forest type and severity may influence the release of Hg during wildfire. This study provides spatial detail on Hg release during fire by developing a model that illustrates the potential for future emissions during high-severity burning and historical emissions from the region using burn severity mapping.

1.1. Literature review of Hg losses resulting from wildfires in the Western United States

There are very few laboratory studies that have examined Hg emission during combustion of fuels from forests of the Western United States. Using litter fuels from a mixture of plant species common to the Western United States, Friedli et al. (2003) reported that the litter released 98% of the initial Hg during combustion. Using measurements of gaseous Hg^0 and CO/CO_2 within a laboratory plume and emission factors (EF; ratio of Hg emitted to biomass consumed) of 14–18 $\mu\text{g-Hg kg-fuel}^{-1}$ were determined for green conifer branches and dry litter, respectively. These laboratory measurements were then compared to wildfires by measuring Hg^0 , and CO/CO_2 as a surrogate for biomass combustion, in the smoke plume of a burning boreal Spruce forest in Ontario, Canada, where an EF of 112 $\mu\text{g-Hg kg-fuel}^{-1}$ was determined. Friedli et al. (2003) attributed discrepancies between lab and field measurements to soil-derived Hg released during heating in the field. In a second study using fuels collected from Western United States locations, Obrist et al. (2007) observed that the moisture content of the fuels greatly influenced the fraction of particulate Hg (PHg) released. Dry fuels emitted almost no PHg, while moist fuels emitted nearly half of the total Hg as PHg. In a study of Hg release from soils during furnace heating, Biswas et al. (2007) measured gaseous Hg^0 from bulk soil collected from 0 to 10 cm depth that were subject to temperatures increasing at a rate of 1 °C s^{-1} from 25 °C to 800 °C. Hg loss from the soil began at 180 °C, which compares well with previous studies reporting that desorption begins at 150 °C from soils containing atmospherically deposited Hg bound by soil humics (Biester and Scholz, 1996). Biswas et al. (2007) also reported that heating at a moderate temperature (180 °C) for 1 h and 4 h resulted in 56% and 91% of Hg being lost from soil, respectively. Considering both temperature and duration of heating suggests that prolonged heating, even at moderate temperatures (<200 °C) is likely to cause Hg release to the atmosphere from soil.

There are a limited number of field-based studies of Hg emissions during wildfires conducted in the Western United States. In a study of the northeastern Sierra Nevada, Engle et al. (2006) reported Hg losses from Ponderosa pine forests and a desert location with sagebrush cover during wildfire and prescribed fire. Engle et al. (2006) classified soil as containing a litter layer and an A-horizon; there is no mention of a separate duff (decomposed litter) layer. The litter layer was found to release >90% of the associated Hg, but there was no loss of Hg measured from underlying soils. To derive areal estimates for emissions during wildfires and prescribed fires, it was assumed that anywhere from 0 to 100% of Hg may be lost from the upper 5 mm of A-horizon soil. Using

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