Wildland fire emissions, carbon, and climate: Emission factors

Shawn Urbanski *

Missoula Fire Sciences Laboratory, Rocky Mountain Research Station, US Forest Service, 5775 US Highway 10 W, Missoula, MT 59808, USA

A R T I C L E   I N F O

A B S T R A C T

While the vast majority of carbon emitted by wildland fires is released as CO_2, CO, and CH_4, wildland fire smoke is nonetheless a rich and complex mixture of gases and aerosols. Primary emissions include significant amounts of CH_4 and aerosol (organic aerosol and black carbon), which are short-lived climate forcers. In addition to CO_2 and short-lived climate forcers, wildland fires release CO, non-methane organic compounds (NMOC), nitrogen oxides ($NO_x = NO + NO_2$), NH_3, and SO_2. These species play a role in radiative forcing through their photochemical processing, which impacts atmospheric levels of CO_2, CH_4, tropospheric O_3, and aerosol. This paper reviews the current state of knowledge regarding the chemical composition of emissions and emission factors for fires in United States vegetation types as pertinent to radiative forcing and climate. Emission factors are critical input for the models used to estimate wildland fire greenhouse gas and aerosol emission inventories.

Published by Elsevier B.V.

1. Introduction

Emissions from wildland fires are a significant source of carbonaceous aerosol, CO, greenhouse gases (CO_2, CH_4), and a vast array of other gases, including non-methane organic compounds (NMOC) (van der Werf et al., 2010; Akagi et al., 2011; Wiedinmyer et al., 2011) (wildland fire is defined as non-agricultural open biomass burning). Inventories of wildland fire emissions are an essential input for atmospheric chemical transport models that are used to understand the role of wildland fires in the atmosphere and climate. An emission factor specifies the amount of a product generated per unit amount of an activity that generates the product. A wildland fire emission factor is usually expressed as the mass of a gas or aerosol species produced per unit mass of vegetation burned (on a dry mass basis). Emission factors are critical inputs for the models used to estimate wildland fire greenhouse gas and aerosol (organic aerosol (OA) and black carbon (BC)) emission inventories (Section 1.1). This chapter reviews the current state of knowledge regarding the chemical composition of fire emissions and emission factors as pertinent to radiative forcing and climate.

1.1. Background

Wildland fire emissions of a species X is typically estimated as the product of area burned (A), fuel loading (FL), combustion completeness (CC), and a specific emission factor (EFX) (Seiler and Crutzen, 1980; Urbanski et al., 2011):

$$E_X = A \times FL \times CC \times EFX \tag{1}$$

* Tel.: +1 406 329 4829.
  E-mail address: surbanski@fs.fed.us

Fuels are defined as biomass (dead and live) that is available for combustion (Sandberg et al., 2001). While most emission models are based on Eq. (1), the source of inputs is highly variable and depends on the purpose of the emission model. Details on how emission models are employed to provide input for air quality and atmospheric chemical modeling may be found elsewhere (Larkin et al., 2009; van der Werf et al., 2010; Urbanski et al., 2011; Wiedinmyer et al., 2011; Larkin et al., 2013, 2014).

Wildland fuels typically have an oven-dry-mass carbon content of 35–55% (Susott, 1996; McMeeking et al., 2009; Burling et al., 2010) and it is the carbon containing emissions (along with a few nitrogen containing species) that have the most significant impact on the chemistry and composition of the atmosphere. The distribution of carbon mass in emissions from fires in temperate conifer forests is shown in Fig. 1. About 95% of the carbon is released as CO_2, CO, and CH_4. CO_2 is a long-lived greenhouse gas and CH_4 is a short-lived climate forcer (Sommers et al., 2012, 2014). The global warming potential of CH_4 relative to CO_2 is 21 on a 100 years time horizon (Solomon et al., 2007). While the vast majority of carbon is emitted as CO_2, wildland fire smoke is nonetheless a rich and complex mixture of gases and aerosols. CO_2 is relatively inert and it is the more reactive, if less abundant, species that are responsible for much of the important atmospheric chemistry. Initial emissions from biomass burning include significant amounts of aerosols that are short-lived climate forcers. The primary aerosols produced by wildland fires are diverse in size, composition, and morphology, and in the consequent chemical and physical properties (McMeeking et al., 2009; Chakrabarty et al., 2010; Levin et al., 2010; Pratt et al., 2011) that impact direct and indirect aerosol radiative forcing (Sommers et al., 2012, 2014). In addition to CO_2 (emissions also include small amounts of the
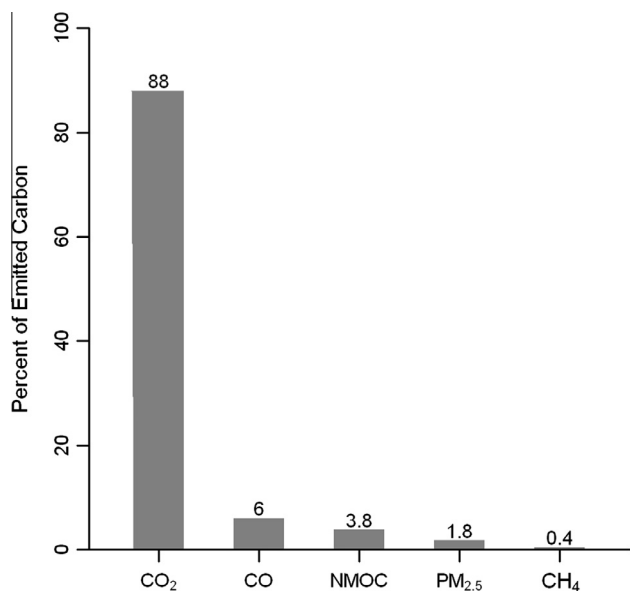
Fig. 1. Partitioning of carbon emissions for pine forest understory prescribed fires. This figure is based on data from Table 2 of Yokelson et al. (2013) and does not consider unidentified NMOC.

Fig. 2. Partitioning of NMOC emissions by carbon number for pine forest understory prescribed fires. This figure is based on data from Table 2 of Yokelson et al. (2013) and does not consider unidentified NMOC.

long-lived greenhouse gas N_2O) and short-lived climate forcers, wildland fires release CO, non-methane organic compounds (NMOC), nitrogen oxides ($NO_x = NO + NO_2$), NH_3, and SO_2. These gases affect radiative forcing through their photochemical processing, which impacts levels of CO_2, CH_4, tropospheric O_3, stratospheric water vapor, and aerosol (Shindell et al., 2009; Heilman et al., 2013). The impact of fire emissions on atmospheric composition and the realized radiative forcing depends on the composition of the emissions, location, and ambient environment (chemical and meteorological). The impact of wildland fire emissions on radiative forcing is complex and highly variable and is beyond the scope of this paper. The reader is referred to Shindell et al. (2009) and Heilman et al. (2013) and references therein for details.

Over 200 gases have been identified in fresh smoke (Yokelson et al., 2013), the vast majority of which are NMOC. The NMOC in wildland fire smoke is distributed across a wide range of compounds with about half the emitted carbon residing in species containing ⩾5 carbon atoms (Fig. 2). Wildland fires are a significant source of NMOC in the global atmosphere (see Akagi et al., 2011 and references therein), despite the fact that these compounds comprise only a small fraction of the total carbon emitted by fires. NMOC play an important role in tropospheric chemistry by contributing to the formation of O_3 and secondary organic aerosol (Alvarado and Prinn, 2009; Yokelson et al., 2009). The production of NMOC by wildland fires is an area of active research. Recent laboratory studies of emissions employing advanced mass spectrometry instrumentation have observed many NMOC which could not be identified, despite state of the art identification methods. In these studies, 31–72% of the NMOC mass detected could not be identified, with high mass compounds (>100 amu) accounting for the largest fraction of unidentified mass (Warneke et al., 2011; Yokelson et al., 2013). These unidentified, high mass compounds are believed to be primarily oxygenated organic compounds or aromatics and are anticipated to play an important role in the formation of aerosol (Warneke et al., 2011).

Fresh smoke aerosol number and mass are principally in fine particulates, $PM_{2.5}$ (particles with an aerodynamic diameter ⩽2.5 μm) (Reid et al., 2005). The majority of particle mass is organic aerosol (OA), but black carbon (BC) and inorganic aerosol (e.g.,
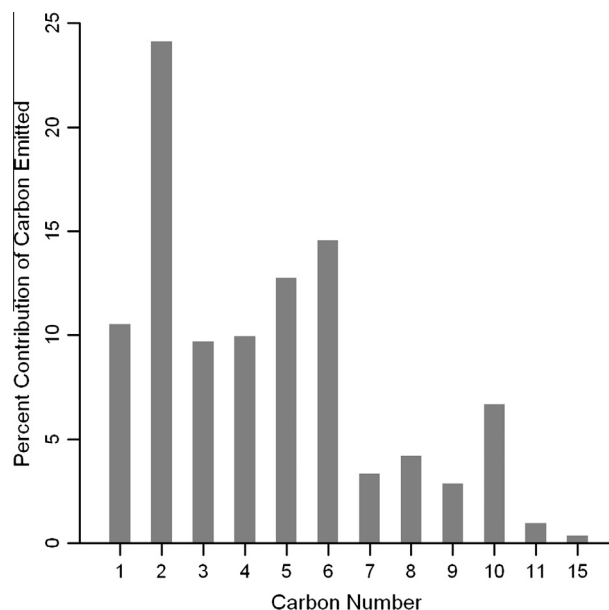
nitrate, sulfate, ammonium, and chloride) generally comprise 5–20% of $PM_{2.5}$ mass (Reid et al., 2005). While the particulate mass emitted by wildland fires is dominated by organic compounds, the individual particles may often be internal mixtures containing organic carbon, elemental carbon, and inorganics (Pratt et al., 2011). These trace inorganic components may have a significant impact on the chemical and physical properties, and hence an important influence on their radiative forcing.

1.2. Terminology

Emission factors (EFs) are critical input for the models used to estimate wildland fire emission inventories (Larkin et al., 2009; van der Werf et al., 2010; Urbanski et al., 2011; Wiedinmyer et al., 2011; Larkin et al., 2012, 2014). EF are determined by measuring the concentration of pollutants in fresh smoke and in the ambient air outside the smoke plume. This section defines the terms associated with the measurement of EF.

1.2.1. Excess mixing ratio
The basic metric used to quantify fire emissions is the excess mixing ratio, which for a species X is defined as $\Delta X = X_{plume} - X_{background}$, where X_{plume} and $X_{background}$ are the mixing ratio of X in the fresh smoke plume and the background air, respectively (Ward and Radke, 1993). Mixing ratio is the ratio of the moles or mass of an atmospheric constituent to the moles or mass of dry air.

1.2.2. Emission ratio
The emission ratio of species X (ER_X) is defined as $ER_X = \Delta X/\Delta Y$ where ΔY is the excess mixing ratio of a smoke tracer, which is a co-emitted species with a reasonably long atmospheric lifetime, typically CO or CO_2. Emission ratios can be used to calculate EF using the carbon mass balance method (Yokelson et al., 1999).

1.2.3. Emission factor
The EF for species X, defined as the mass of X emitted per mass of dry biomass consumed, in units of $g\,kg^{-1}$, may be estimated using (Yokelson et al., 1999):