Forest Ecology and Management 317 (2014) 61–69

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Wildland fire emissions, carbon, and climate: U.S. emissions inventories

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ARTICLE INFO

Article history:
Available online 1 November 2013

Keywords:
Fire emissions
Emissions inventories
Greenhouse gases

ABSTRACT

Emissions from wildland fire are both highly variable and highly uncertain over a wide range of temporal and spatial scales. Wildland fire emissions change considerably due to fluctuations from year to year with overall fire season severity, from season to season as different regions pass in and out of wildfire and prescribed fire periods, and from day to day as weather patterns affect large wildfire growth events and prescribed fire windows. Emissions from wildland fire are highly uncertain in that every component used to calculate wildland fire emissions is uncertain – including how much fire occurs and at what time during the year, assessments of available fuel stocks, consumption efficiency, and emissions factors used to calculate the final emissions. As shown here, these component uncertainties result in large-scale differences between estimation methods of wildland fire emissions including greenhouse gas totals, particulate matter totals, and other emissions. Four recent emissions inventories for the contiguous United States are compared to determine inter-inventory differences and to examine how methodological choices result in different annual totals and patterns of temporal and spatial variability. Inter-model variability is detailed for several current models, and current knowledge gaps and future directions for progressing fire emissions inventories are discussed.

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1. Introduction/background

Fire emissions are gases and particulates released during all phases of combustion. Wildland fire emissions include fine particulate matter (⩽2.5 microns, $PM_{2.5}$), black carbon (BC), carbon dioxide (CO_2), carbon monoxide (CO), and other trace gases (Urbanski et al., 2008). These emissions affect both air quality (e.g., Wotawa and Trainer, 2000) and global climate (e.g., Crutzen and Andreae, 1990). Large amounts of CO_2 are emitted annually around the globe during biomass burning (Andreae and Merlet, 2001). In addition to CO_2, trace gases methane, nitrous oxide, and other climate forcing compounds (Houghton et al., 1996) are emitted during both the flaming and smoldering phases of combustion (Fearnside, 2000). Their ratios relative to emitted CO_2 differ depending on fuel type, moisture, and combustion phase (Akagi et al., 2011). Wildfires are episodic events that can emit significant amounts of $PM_{2.5}$ into the atmosphere (Hodzic et al., 2007), which can then alter the natural radiative forcing through additional scattering and/or absorption (e.g., Shekar Reddy and Venkataraman, 2000). Black carbon emitted from wildfire can be deposited on snow and ice leading to albedo changes and feedbacks that can contribute significantly to radiative forcing changes, particularly in the Arctic (Hansen and Nazarenko, 2004; Quinn et al., 2008). Quantification of biomass emissions is required to understand the impact of fire on climate (Larkin et al., 2010) and to predict poor air quality during an ongoing biomass burning event (O'Neill et al., 2009; Strand et al., 2012).

Emission inventories are developed to quantify emissions from various activities and natural processes. Fire emissions inventories are used within models to predict regional air quality during ongoing biomass burning, to quantify shifts in atmospheric chemistry due to the sudden influx of particulates and gases, and to ascertain the impact of fire on climate (e.g. Wiedinmyer et al., 2006). These inventories are developed to assist with the understanding of current emission trends and are often the basis for policy decisions such as regulation and permitting. Unlike most other emissions sources, wildland fires are highly episodic across both the spatial and temporal scales (Liu, 2004). Wildland fire emissions change considerably due to yearly fluctuations of overall fire season severity, seasonally as regions pass in and out of wildfire and prescribed fire periods, and daily due to synoptic weather patterns that affect large wildfire growth events and prescribed fire windows. This variability is also reflected spatially within the United States throughout the year. On smaller spatial scales (~km), the variability in emissions is evident across ridges and valleys that face different directions as solar radiation affects fuel moisture and type of vegetation cover. The spatial and temporal variability in emissions

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0378-1127/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.foreco.2013.09.012

makes fire emission inventory development difficult, and there is often a wide range of uncertainty associated with wildfire emission inventories.

In the following text we discuss the process of computing a fire emissions inventory and address the sources of uncertainty in such inventories, using four emissions inventories created for the contiguous United States (CONUS) as a test case example: the United States Environmental Protection Agency National Emissions Inventory (US EPA NEI), the Global Fire Emissions Database (GFED), the Fire INventory NCAR (FINN), and the US EPA Greenhouse Gas Inventory (US EPA GHG). It is important to note that each of these emissions inventories was developed to serve a different purpose: the NEI is a national accounting of emissions developed for use in modeling for national regulatory and policy purposes among other uses; GFED and FINN were designed for use in continental and global modeling of the atmosphere and modeling of chemical processes; and the EPA GHG inventory is specifically designed to meet the requirements for reporting national aggregate emissions to the United Nations Framework Convention on Climate Change, which includes specifics on what types of fires are to be included in the inventory. Nonetheless, these four inventories are modern representations of wildland fire emissions over CONUS and a comparison of their similarities and differences, and how these arise from methodological choices within each inventory, illustrates the difficulties in both developing, and in using, fire emissions inventories.

1.1. Scope and objectives

We examine here the fundamentals of how fire emissions and fire emissions inventories are calculated, and how different choices made in creating fire emissions inventories underpin their differences. Four current emissions inventories are examined including their inter-annual and seasonal variability. Inter-model variability is detailed for several current models, and current knowledge gaps and future directions for progressing fire emissions inventories are discussed.

The focus of this discussion is CONUS because this region has significant observational data, yet also shows the difficulties in creating fire emissions inventories that encompass different types of fire, ecosystems, and burning seasons. In addition, the availability of reporting systems that record fire location, size, and duration varies considerably across the many different land owners (private, federal, state, tribal, etc.) and fire types found in this region. Finally, many models of fuels, fire consumption, and fire emissions have been developed for application within CONUS, allowing for illustration of the uncertainties involved in current fire emission inventory development. The relative wealth of officially reported information and models compared to other regions highlights difficulties even in the most well monitored and studied ecosystems.

It is worth noting that much of the U.S. effort in developing emissions inventories and their component models and datasets (e.g. of fire information, available fuels, consumption models, and emissions factors) has been driven less by the need to report greenhouse gases (e.g. per international agreements), and more by the operational needs of land management (e.g. to account for activities on managed lands), as well as needs arising from laws and regulations governing air quality. The U.S. has a complex system of air quality regulations stemming from the 1972 Clean Air Act that identify required ambient air quality standards for certain pollutants, including particulate matter and ozone, and also mandate long-term planning to ensure visibility in protected airsheds such as within the U.S. National Park system. Fires, particularly large wildfires, significantly and adversely affect the values protected by these standards, and so accounting for wildland fire emissions is important in meeting and/or claiming exceptions to air quality targets that can have fiscal penalties if not met.

1.2. Calculating fire emissions

Calculation of fire emissions can be understood (Eq. (1), adapted from Seiler and Crutzen, 1980) as combining information on the size of the fire (***A***), the available biomass (***B***, per unit area) from the location of the fire, the relative consumption (***C***, as a % of the biomass) that occurred, and the emissions factor for the particular species of interest (***EF$_i$***).

$$\text{Amount of Species}_i \text{ Emitted} = A * B * C * EF_i \quad (1)$$

The size of the fire can be taken from any number of sources including ground reports, helicopter perimeters, ground or satellite measurement of burn scars, and planning documents for prescribed burns. It can also be inferred from satellite hot spot detections and intensity measurements (see also Hao and Larkin, 2014). The available biomass can be taken from local knowledge of the ecology, comparisons with photographs of known fuel loadings, detailed measurements such as LiDAR or plot measurements, and/or mapped fuel loading data that combine intensive local measurements with satellite maps to allocate fuels across the landscape (see also Weise and wright, 2014). Consumption is typically modeled using relationships derived from observations collected both pre- and post-burn to relate overall consumption to parameters such as fuel moisture, wind, and season (see also Ottmar, 2014). The emissions factor is then applied to determine the amount of the specific species of interest emitted (see also Urbanski, 2014). It is worth noting that, in general, the percentage consumed can also be related to the available biomass (***B***), and the specific emissions factor to use can be related to both the biomass type and the overall consumption efficiency; these connections make the above equation less separable than it appears.

An alternative to Eq. (1) is to use measures of fire intensity, typically as detected by satellites, to determine fire emissions. This method uses an empirical relationship that relates emissions to detected fire radiative energy, estimated from instantaneous satellite-based measurements of fire radiative power. The relationships are typically developed by region and vegetation type and bypass the need to more explicitly know the underlying biomass and calculate consumption, resulting in a simplified equation: $Emissions = C_e * R_{fre}$, where C_e is a region specific emissions coefficient and R_{fre} is the rate of release of radiative energy (Ichoku and Kaufman, 2005).

1.2.1. Fire emissions inventories

To create a fire emissions inventory, the above suite of methods must be pared down to a specific methodological choice (Table 1). The choice of which fire occurrence dataset, biomass dataset, consumption model, and emissions factors to use all affect the final emissions inventory, as shown below. Perhaps the clearest choice involves which fire occurrence dataset to use, as this directly controls the area covered (e.g., a particular state or the area observed by a particular satellite), the types of fire covered (e.g. wildfires, prescribed fires and/or agricultural fires), and other limitations (e.g., ability to detect small fires) of the final emissions inventory. However, other choices, such as the specific choice of fuel loading maps or the specific collected set of fire emissions factors used, may affect the final result as much, but be less tractable.

Fire emissions inventories, particularly those used in air quality modeling, need to specify emissions by hour; this is because the specific location(s) of air quality impacts will move as the transport winds, lofting height and rate of the emissions change throughout