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Wildland fire emissions, carbon, and climate: Science overview and knowledge needs

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ABSTRACT

Wildland fires have influenced the global carbon cycle for ~420 million years of Earth history, interacting with climate to define vegetation characteristics and distributions, trigger abrupt ecosystem shifts, and move carbon among terrestrial and atmospheric pools. Carbon dioxide (CO_2) is the dominant driver of ongoing climate change and the principal emissions component of wildland fires, while black carbon and other aerosols found in fire emissions contribute to uncertainties in climate projections. Fire emissions research to date has been focused on developing knowledge for air pollution regulatory needs and for assessing global climate impacts. Quantifying wildland fire emissions is difficult because their amount and chemical composition vary greatly among fires depending on the amount and type of combusted fuel, its structure, arrangement, chemistry, and condition, and meteorological conditions during the fire. Prediction of potential future wildland fire emissions requires integration of complex interactions of climate, fire, and vegetation; e.g., inference about the direct effects of climate changes on vegetation (fuel) distribution, amount, and condition; direct effects on fire occurrence, behavior, and effects; and feedbacks of altered fire regimes to vegetation and the climate system. Proposed climate change mitigation strategies include management of forests for increased carbon sequestration, and because wildland fires are a key component of the carbon cycle, fire ecology, behavior, and fire effects must be accounted for in these strategies. An understanding of the complex relationships and feedbacks among climate, fire regimes, and fire emissions is needed to account for the importance of fire in the carbon cycle and wildfire and carbon feedbacks to the global climate system. Fire ecology and fire emissions science is thus a necessary component for adaptively managing landscapes and for accurately assessing the long-term effectiveness of carbon sequestration projects. This overview for a special issue on wildland fire emissions, carbon, and climate summarizes eight companion papers that describe the current state of knowledge, critical knowledge gaps, and importance of fire emissions for global climate and terrestrial carbon cycling. The goal is to foster understanding of complex fire emission system dynamics and feedbacks.

1. Background

Fire has influenced carbon cycling and interacted with the climate system for ~420 million years of Earth history (Bowman et al., 2009). Fire is a natural disturbance process that accelerates or triggers ecosystem change, shapes long-term vegetation distributions and characteristics, impacts productivity and biodiversity, and moves carbon among terrestrial and atmospheric pools (i.e., the carbon cycle) (Schimel, 1995; Seiler and Crutzen, 1980; Whitlock et al., 2003). Photosynthetic fixation of carbon dioxide (CO_2) by green plants and other autotrophs sustains life on Earth by moving carbon from atmospheric to terrestrial pools, and by helping to regulate the global climate (Braakman and Smith, 2012; Lenton et al., 2012). While atmospheric CO_2 is *regulated* at geologic time scales by mechanisms such as outgassing and weathering, more than one third of the CO_2 currently in the atmosphere is *exchanged* annually with the biosphere, making terrestrial ecosystems a dynamic component of the global carbon cycle (Pälike et al., 2012; Sitch et al., 2008, 2003). Wildfires play a major role in the release of terrestrial carbon from stored pools to other locations within ecosystems and to the atmosphere (Kasischke et al., 2000a,b; Urbanski et al., 2009a,b). Fire emissions that transfer carbon to the atmosphere are an inherent product of the combustion of vegetation (fuel) and a key pathway for the flux of carbon between forests and the atmosphere (van der Werf et al., 2010). Wildfires in forested regions are a critical link in the global carbon

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cycle, as forests store about 45% of terrestrial carbon and may sequester up to 25% of annual anthropogenic carbon emissions (Anderegg et al., 2012; Pan et al., 2011).

Concerns about current and projected changes in global climate have raised an expectation that forests can help mitigate climate changes via management for increased carbon sequestration and storage (Canadell and Raupach, 2008; Haverd et al., 2013; Keith et al., 2009; Mackey et al., 2013; Millar et al., 2007; Pechony and Shindell, 2010; Williams, 2013). However, climate changes are likely to increase wildfire frequency, extent, and severity in forested ecosystems, thus influencing forest carbon dynamics and sequestration potential (Coumou and Robinson, 2013; Diffenbaugh and Field, 2013; Flannigan et al., 2013; Hurteau and Brooks, 2011; Raymond and McKenzie, 2012; van Mantgem et al., 2013). Comprehensive knowledge of fire emissions is needed to effectively quantify and assess the changing role of fire in the carbon cycle, including feedbacks to climate change (Denman et al., 2007; Jacob and Winner, 2009; Meigs et al., 2011; Stocks et al., 1998; Zhu et al., 2010). Fire emissions knowledge is thus a necessary component for adaptively managing forest ecosystems and for accurately assessing the long-term benefits of carbon sequestration projects (GOFC, 2009; Miller et al., 2012; Peterson et al., 2011).

Fire emissions research to date has been focused on two main topics: smoke management for air pollution regulatory needs, and global climate impacts (Ottmar, 2001; Prentice et al., 2011). For example, air pollution concerns were addressed by Sandberg et al. (2002) in a state-of-knowledge review about the effects of fire on air quality, developed to assist land, fire, and air resource managers with fire and smoke planning. A recent body of research has contributed to our understanding of the role of fire in the global carbon cycle, its relationship to climate change, and fire–climate feedback mechanisms (Bowman et al., 2009; Moritz et al., 2012). Emissions data have been used to estimate the contribution of regional fire activity to carbon cycling, with implications for forest carbon management (Campbell et al., 2007; North and Hurteau, 2011; Wiedinmyer and Neff, 2007). Quantifying or predicting wildland fire emissions is difficult since their amount and character vary greatly from fire to fire, depending on such factors as biomass carbon densities, quantity and condition of consumed fuels, combustion efficiency, and weather (Ottmar et al., 2008; Stoof et al., 2013). Further, emissions measured for an individual fire event may not be characteristic of landscape-scale emissions potential, due to complex ecological patterning and spatial heterogeneity of burn severity within fire perimeters (Turner and Romme, 1994; Turner, 2010). Recent policy statements (e.g., Association for Fire Ecology et al. (2013)) on climate, wildland fires, and carbon make it timely to examine how emissions of greenhouse gases and aerosols generated by wildland fires link forest carbon cycling and atmospheric climate change processes (Fig. 1).

The articles in this issue of *Forest Ecology and Management* synthesize what we know about the interactions of wildland fires and fire emissions, the global carbon cycle, and the climate system. Topics include fire regimes of forested ecosystems, fire activity and burned area, wildland fuels and fuel consumption, emissions factors and inventories, atmospheric transport and chemistry, and climate-driven changes in wildfires. We further identify knowledge gaps within each of these topics that currently limit our understanding of the role of wildland fire in the movement of terrestrial carbon as emissions to the atmosphere and in sequestration by ecosystems.

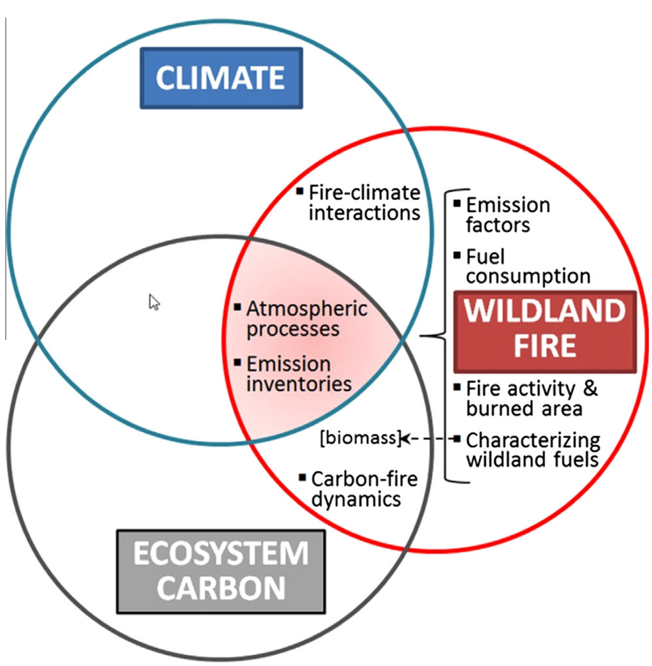

Fig. 1. Wildland fire emissions are part of a dynamic mechanism linking core fire and fuel processes (wildland fire), carbon cycling (Ecosystem Carbon), and climate (climate). Multiple non-linear feedback loops add complexity to the component interactions. Bulleted items in the figure are explicitly addressed in this overview as well as in each of eight respective papers associated with this special issue.

2. The climate–fire–carbon pathway

2.1. Ecosystems and fire regimes

Globally, forests contain the Earth's largest terrestrial carbon stocks, with an estimated total annual global forest carbon sink of ~2.4 Pg C yr^{-1} (Pan et al., 2011). The carbon sequestration potential of Earth's forests is about 33% of global anthropogenic emissions from fossil fuels and land use (Denman et al., 2007), and within the United States alone forests represent 89% of the national terrestrial carbon sink and offset about 13% of annual continental fossil fuel emissions (King et al., 2007; North and Hurteau, 2011; Pacala et al., 2007; Pan et al., 2011). For the conterminous Untied States and Alaska, current estimated carbon stocks are 57,000 TgC for forests; 16,000 TgC for grasslands/shrublands and 20,000 TgC for croplands (Zhu et al., 2010). This synthesis is focused on wildland fires and does not include emissions from croplands, which contribute significantly to the total area burned by prescribed fires in the United States (Melvin, 2012).

Wildland fires in forested ecosystems are one of the primary mechanisms that regulate patterns of carbon storage and release (Kasischke et al., 2000a,b). When wildland fires occur, biomass is converted to carbon emissions, water, and energy, with the amount of biomass consumption and carbon release dependent on wildland fire extent and combustion characteristics; these in turn are driven by pre-disturbance site conditions and productivity, and the organizing influence of climate (Bigler et al., 2005; Dale et al., 2001; Falk et al., 2007). Thus, release of carbon from wildland fires is climate- and disturbance regime-dependent and is highly ecosystem specific (Keith et al., 2009).

The role of fire in ecosystems and its interactions with dominant vegetation is termed a fire regime (Agee, 1993). Fire regimes describe general characteristics of wildland fires such as frequency (mean number of fires per time period), extent, intensity (measure of the heat energy released), severity (net ecological impact), and seasonal timing. As described in an accompanying paper in this journal on carbon-wildland fire dynamics (Loehman et al., 2014), carbon emissions vary with fire regimes. For example, high-severity fires may consume most aboveground biomass, resulting in an instantaneous pulse of carbon; however, these fires typically