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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).

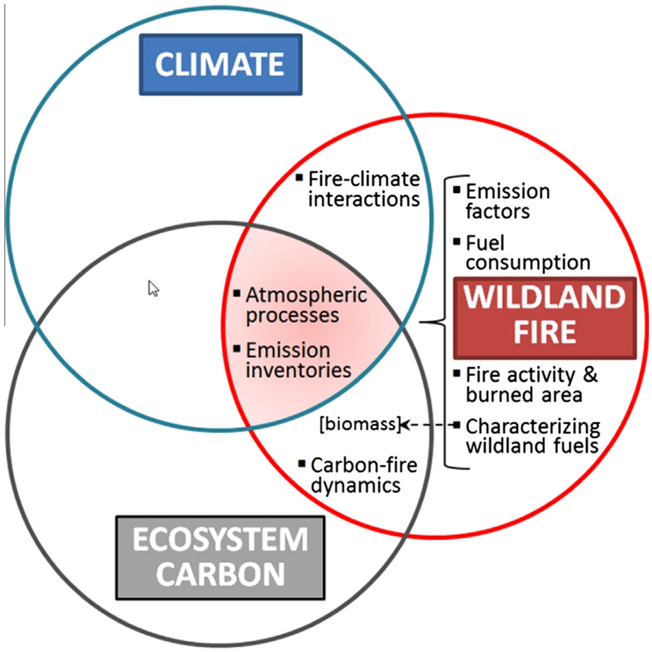

Fig. 1. Wildland fire emissions are part of a dynamic mechanism linking core fire and fuel processes (wildland fire), carbon cycling (Ecosystem Carbon), and climate (climate). Multiple non-linear feedback loops add complexity to the component interactions. Bulleted items in the figure are explicitly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

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.

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 $\sim$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 occur infrequently, affording long-term carbon storage in woody biomass when forests regrow. Low-severity fires typically release less carbon per fire event (although total emissions are dependent on area burned) at more frequent intervals than with stand-replacing regimes, and favor long-lived and fire-resistant (or tolerant) forest species that typically survive multiple fire events (Ritchie et al., 2007). Carbon losses from wildland fire are balanced by carbon capture from forest regrowth across unmanaged fire regimes and over long time periods (e.g., multiple decades) unless a lasting shift in plant community type occurs and/or fire return intervals change (Kashian et al., 2006; Wiedinmyer and Neff, 2007). Current research suggests that climate changes may increase wildfire frequency, extent, and amount of high-severity fire (Dillon et al., 2011; Flannigan et al., 2006; McKenzie et al., 2004). Changes in fire regimes may be accompanied by persistent shifts in vegetation composition and structure, and concomitant shifts in carbon storage and sequestration potential (Loehman et al., 2011; Westerling et al., 2011).

Our abilities to assess future wildland fire emissions and terrestrial carbon dynamics are limited by our lack of understanding of key fundamental mechanisms and complex interactions. First, because current fire prediction systems are semi-empirical models, based largely on observations of ignition probabilities and fire spread under current climate and fire weather conditions, they may not be capable of modeling fire behavior in future fire environments. Second, we lack comprehensive understanding of the effects of interacting and synergistic disturbance processes (e.g., climate changes, wildfires, and insect and disease activity) on ecosystems. These include potential ecological thresholds, non-linear responses, and feedbacks that may result in dramatic changes in landscape function and form, and in carbon emissions and storage. Two complementary strategies can improve carbon assessments, especially in the context of climate changes: (1) enhanced monitoring programs that improve our understanding of long-term, landscape-scale ecological responses to fire, provide data to evaluate effectiveness of management activities, and identify key emerging ecological dynamics; and (2) modeling platforms that mechanistically simulate climate, atmosphere, vegetation, and wildland fire interactions and emergent behaviors, accounting for changes in combustion and emissions at landscape scales.

2.2. Fire activity and burned area

Quantification of fire emissions relies on identification of fire occurrence over time (fire activity) and the area of consumed biomass (burned area) (Hao and Larkin, 2014), information needed to accurately assess the relative importance of fires as a source of greenhouse gases, aerosols, and black carbon that impact climate (Bond et al., 2013). Fire emissions are highly variable in time and space and depend on ecosystem and atmospheric conditions and interactions; thus, assessing the relative climate response as compared to other sources is difficult (van der Werf et al., 2010). Seiler and Crutzen (1980) published the first estimates of global charcoal production and atmospheric emissions of trace gases volatilized by burning, based on the amount of biomass affected by fires. They estimated a worldwide average burning efficiency of about 50%, with a carbon sink for atmospheric CO_2 due to incomplete combustion of biomass to charcoal. The scarcity of reliable, complete information on fire patterns and consumed biomass at the time of the study resulted in a large uncertainty in estimations of biosphere effects on the atmospheric CO_2 budget (calculations ranged from a net uptake or a net release of about 2 Pg C/yr). Hao and Liu (1994) provided the first geospatially gridded, monthly biomass burning inventory based on United Nations Food and Agricultural Organization (FAO) statistics and other published sources. They found that because of the dominance of savanna fires in tropical Africa about twice as much biomass is burned there as in tropical America (Central and South America). This figure differed from earlier estimates that ~80% of the area burned globally occurred in the tropics (Seiler and Crutzen, 1980).

Since the late 1990s, satellite-based observations have become a major input for calculations of fire emissions, especially using data from NASA's MODIS (MODerate Resolution Imaging Spectroradiometer) sensor onboard Terra and Aqua satellites (Hao and Larkin, 2014). Although active MODIS fire detection became available shortly after satellite launch, burned area estimates were not available until Giglio et al. (2005) calculated monthly burned areas for the period 2001–2004. Since then, considerable advancement in remotely sensed burned area estimation has taken place (Giglio et al., 2009; Roy et al., 2008; Urbanski et al., 2009a,b, 2011). Estimations of the annual burned area over the – western United States for the period 20032008 varied by almost an order of magnitude, from a low of $3.6 \times 10^3\ \text{km}^2$ in 2004 to a high of $1.9 \times 10^4\ \text{km}^2$ in 2007, with burned areas in different states differing by orders of magnitude for different years (Urbanski et al., 2011). This high degree of spatial and temporal variability highlights the complexity in predicting trends in burned area in response to changing climate.

Hao and Larkin (2014) describe the considerable recent progress that has been made mapping the spatial and temporal extent of wildland fires, and the expectation for further advances as new remotely sensed and land-based measurement technologies become available. However, they note a particular need for better characterization of prescribed fires – these are not easily mapped by satellite-based sensors because they are typically of small size and duration and burn beneath forest canopy, but are of significant regional and local air quality importance. More research is needed to identify major factors that influence seasonal and interannual variability in burned area for different ecosystems, improve prescribed fire and agricultural burning datasets, and to project effects of climate changes on fire activity and burned area in the coming decades.

2.3. Fuel consumption and characterization

The amount and type of carbon-containing emissions from wildland fire depend on fuel *consumption* (e.g., the amounts of various component fuels consumed by fire) and fuel *characterization* (e.g., fuel type, fuel load, and moisture condition) (French et al., 2011; Ottmar, 2014). Fuel is the live and dead vegetation available to burn in wildland fires. Release of specific emissions components including greenhouse gases, aerosols, black carbon, and organic carbon is determined by fuel properties and their various interactions within the consumption process. Because actual fuel consumption depends on highly complex and variable combustion phase-dependent conditions, fuel consumption estimates can be a significant source of errors in estimates of greenhouse gas emissions from wildland fires (French et al., 2004). Many empirical studies have expanded our understanding of fuel consumption in recent years, driven both by interest in the basic fire processes and by questions regarding the efficacy of using fuel treatments for wildland fire hazard reduction (Reinhardt et al., 2008).

Although significant progress in quantifying fuel consumption has been achieved over the past 30 years, studies targeting consumption of specific fuelbed categories such as tree and shrub canopies, deep organic layers, and large rotten logs are limited. Further, fuel moisture prediction models, an important variable for predicting fuel consumption, are poor, especially for the large woody fuels and organic soils. As we move forward with advanced remote sensing techniques, large scale estimates of greenhouse gas emissions will not improve unless we find ways to better link fuels and consumption to remote sensed data. This may include sensing of wildland fire severity and relating that to fuel consumption, or interpreting both the physical and moisture attributes. Finally, additional research is needed to better understand the charred residues and ash remaining after fires and how much of that material becomes sequestered carbon to offset the emissions of greenhouse gases (Ottmar, 2014).

Fuel characterization has traditionally served as a main input component for fire danger, fire behavior, and fire spread models, but has not been formulated to include the exceptional complexity of actual wildland fuels (Deeming and Brown, 1975; Finney, 1998; Keane, 2012; Rothermel, 1972). Two primary fuels classification systems currently provide information designed to aid in estimating fuel consumption and emissions: the Fuel Characteristic Classification System (FCCS), which provides a detailed characterization of fuels across six strata (canopy, shrubs, herbs and grasses, dead and down woody debris, and litter, which includes lichens and mosses, and duff or ground fuels) (Ottmar et al., 2007; Sandberg et al., 2001); and Fuel Loading Models (FLMs), a classification of fuel beds based on advanced clustering and regression tree statistical techniques (Lutes et al., 2009). The FLM classification used field-collected fuel loading data to simulate smoke emissions and soil heating, the results of which were then used to create the FLM clusters. An accompanying article (Weise and Wright, 2014) provides a detailed synthesis of wildland fuel characterization. Although fuels have been characterized for many ecosystems, there are still many types that are poorly described. For example, very little research has been conducted to document fuel characteristics in short grass prairies and many wetland ecosystems (Wade et al., 1979; Wendel et al., 1962). In addition, some fuelbed components, such as belowground and soil fuels, are not well described or quantified. Further, relationships among fuel characteristics, fuel consumption, and emissions are not well quantified for several fuel components, including tree crowns, live shrubs, and belowground biomass. Fuel characterization is a critical component for understanding how climate changes will affect fire in the future, because novel vegetation and fuel assemblages that might arise under an altered climate regime could affect area burned, combustion efficiency, fuel loading, fuel consumption and, ultimately, greenhouse gas, aerosol, and black carbon emissions (Abatzoglou and Kolden, 2011; Schoennagel et al., 2004).

2.4. Fire emission factors and inventories

An emission factor is a measure of the average amount of a specific pollutant or material discharged into the atmosphere by a process, such as fire. Once established, emissions factors allow for an *inventory* of emissions for sources of gases and aerosols in a given area for a specified time period, based on consumed fuel characteristics (Andreae and Merlet, 2001). Emissions factors are a critical input for the models used to estimate the contributions of greenhouse gases and aerosols from wildland fire (Urbanski, 2014). The impact of fire emissions on radiative forcing and greenhouse warming depends on the composition of the emissions, which in turn is influenced by fuel structure and arrangement, fuel chemistry, fuel condition, and meteorology, factors that ultimately govern how a fire burns. Urbanski (2014) summarizes the composition of emissions and emissions factors pertinent to radiative forcing and climate, for US vegetation types. Chemical species released by wildland fires include CO_2, carbon monoxide (CO), and methan (CH_4), organic aerosols and black carbon, non-methane organic compounds, nitrogen oxides (NO_x), and sulfur dioxide (SO_2). The chemical composition of smoke is also related to the amount of smoldering and flaming combustion that occurs during the fire; for example, flaming combustion typical of burning of fine woody fuels, grass, litter, and foliage produces CO_2, nitrogen oxide (NO), and nitrogen dioxide (NO_2), among others, while smoldering combustion of large-diameter woody fuels and ground fuels produces CO, CH_4, and ammonia (NH_3).

Urbanski (2014) identifies significant gaps in the development of emission factors in four areas: wildfires in temperate forests, residual smoldering combustion, aerosol speciation, and nitrogen containing compounds. Filling these knowledge gaps, and reducing uncertainty in characterization of fire emissions and smoke composition, will improve our understanding of fire contributions to the global carbon cycle. Few field measurements of temperate forest wildfire emission factors exist, and proxy factors developed from prescribed fires may underestimate emissions from consumption of smoldering fuels. Emissions data for residual smoldering combustion smoldering combustion process that is no longer influenced by strong convection associated with a flame front (Wade and Lunsford, 1989) are mainly from laboratory studies, and there is a significant need for field measurements to extend the application of these data to fires in natural environments. The nitrogen content of fuels consumed by wildland fires is highly variable, and thus the emissions for a specific region, vegetation type, or fire event can differ substantially from the best emission factors compiled to date. Finally, field measurements of emission factors for black carbon and organic aerosols are needed. Although much recent laboratory work has been done to characterize particle emissions (e.g., Chen et al., 2006, 2007; Levin et al., 2010; McMeeking et al., 2009), the applicability of these measurements to natural fires is uncertain (Akagi et al., 2011).

Larkin et al. (2014) describe development, use, and inherent uncertainties of emission inventories. Emission inventories quantify emissions from various activities and natural processes, such as prescribed and wildland fires. Fire emission inventories are used within models to predict regional air quality, quantify shifts in atmospheric chemistry, and estimate the impact of fire on climate, and are often the basis for environmental regulation and permitting. Calculations of fire emissions are made by combining information on fire size, the available biomass per unit area, the relative consumption of biomass that occurred, and the emissions factor for the particular chemical species of interest. Wildland fires are unlike most other emissions sources (e.g., industry) because they are highly episodic in space and time (Liu, 2004); wildland fire emissions are thus difficult to monitor, predict, or integrate into regional or global-scale inventories.

Advances in satellite observation have enabled the development of broad-scale emission inventories based on burned area estimates and published emission factors for major chemical species of interest (Hoelzemann et al., 2004). In their examination of four current emissions inventories for the continental United States, Larkin et al. (2014) identify three critical knowledge gaps: basic fire information, fuel characterization, and emissions produced from deep organic fires. Fire area remains the single largest factor affecting emissions inventories, including identification of fires eligible for inclusion in the inventory and accurate detection and characterization of burned areas. Heterogeneity of fuels (loading, vertical and horizontal arrangement) is a large contributor to variability (hence, uncertainty) within emissions inventories, and available fuel loading varies greatly among modern fuel loading databases. In addition, current fuel loading maps used in fire emissions inventories are static, accounting for neither seasonal changes nor disturbances such as fires or land use changes that occurred since the map was made. Regions with deep organic layers, (e.g., southeastern United States, Alaska) have the potential to emit large quantities of particulates and greenhouse gases when these layers burn. Very few studies have been conducted to characterize and quantify the suite of emissions produced from deep organic fires, and current models do a poor job of characterizing their emissions.

2.5. Fate of emissions within the atmosphere

Carbon emitted from wildland fires enters the atmosphere and undergoes complex processes that determine its post-emission disposition. As noted by Heilman et al. (2014), assessing the fate of fire emissions requires knowledge of chemical composition, time-dependent transformation, vertical and horizontal transport, atmospheric residence time and removal processes, and radiative forcing characteristics. 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). Research on emissions in the atmosphere has been motivated primarily by local and regional air quality concerns, including impacts to transportation systems, visibility, and human health (Phuleria, 2005; Pyne, 2004; Sandberg et al., 2002; Stefanidou et al., 2008). Satellite imagery has highlighted the global extent and transport of fire emissions, including long range smoke impacts caused by recent, very large fires (Conard and Ivanova, 1997; Damoah et al., 2004; Fromm et al., 2010, 2006; van Donkelaar et al., 2011). Bond et al. (2013) described the important feedbacks of aerosols including black and organic carbon to the climate system, thus expanding the relevance of emissions research.

The body of knowledge on atmospheric processes involved in the transport and chemical make-up of smoke plumes is substantial. However, new modeling and observational research is still needed to address shortcomings in our understanding of fundamental fire-fuel-atmosphere interactions. Plume rise is determined by multiple factors, including fuel characteristics, fire behavior, emissions, canopy structure, fire-induced and ambient turbulence regimes, and atmospheric conditions. Comprehensive field measurements of these factors, using *in situ*, upper-air, and down-wind instruments deployed during wildland fire events, are needed to characterize local and downwind plume behavior. A suite of observational datasets are also needed to compare and validate the performance of current and future smoke-plume dynamics models. An additional, significant knowledge gap relates to the formation of secondary organic aerosols during combustion, observed to be highly variable in space and time. Filling this knowledge gap will require a better characterization of emissions and plume chemistry and an improved understanding of the influence of plume dynamics (rise, dilution, and cooling) and background chemical composition (e.g., urban or rural chemical environment).

2.6. Climate–fire interactions

Weather and climate have long been known to be of great importance to wildland fire behavior (Beals, 1916, 1914; Schroeder and Buck, 1970; Schroeder et al., 1964) but have historically been considered as unidirectional, independent variables with respect to fire (e.g., they affect emissions, but interactions have been neglected). As awareness of anthropogenic climate change has increased, interest in interactions of climate and fire has grown (Pausas and Fernández-Muñoz, 2011; Randerson et al., 2006). An accompanying article (Liu et al., 2014) provides a synthesis of information on climate–fire interactions, with a special focus on the role of fire emissions as climate forcers. Climate forcers are gases and particles in the atmosphere that alter the Earth's energy balance by absorbing or reflecting radiation. The relative impact of a particular climate forcer depends on factors such as how efficiently it absorbs radiation, its atmospheric concentration, and its residence time in the atmosphere.

Fire emissions contribute to climate change by: (1) increasing greenhouse gas concentrations, thereby increasing atmospheric radiative forcing, (2) increasing aerosol concentrations, thereby increasing reflectivity of incoming solar energy, and (3) changing the Earth's albedo by depositing more light absorbing particles (e.g., black carbon) at the Earth's surface (Arrhenius, 1908; Seiler and Crutzen, 1980; Twomey, 1977). Emission factor estimates identify CO_2 as the trace gas species most heavily emitted by biomass burning (Andreae and Merlet, 2001); CO_2 is also the dominant greenhouse gas contributor to global climate change because of its heat absorbing characteristics and very long residence time in the atmosphere (Lacis et al., 2010). Anthropogenic emissions of CO_2 since the Industrial Revolution ca. 1750, as a byproduct of combustion of carbon-containing fuels, have contributed to a 40% increase in the atmospheric concentration of carbon dioxide from 280 to 392.6 parts-per-million (ppm) in 2012 (Blasing and Smith, 2013). Biomass emissions are the second largest source of trace gases (after fossil fuel emissions) and the largest source of primary fine carbonaceous particles in the global troposphere (Akagi et al., 2011). At current emission rates, concentration of atmospheric CO_2 will be ~1000 ppm by the end of this century, resulting in irreversible long-term warming (Solomon et al., 2009). Global climate models predict an average annual global temperature increase of 1.4–3.0 °C by 2050 (relative to the 1961–1990 global average) under a mid-range carbon-forcing scenario (Rowlands et al., 2012). This amount of warming is predicted to increase wildfire frequency and extent, and the area of high-severity fire (Dillon et al., 2011; Flannigan et al., 2006; McKenzie et al., 2004), in turn increasing wildland fire emissions (Spracklen et al., 2009).

Many knowledge gaps contribute to uncertainties in our understanding of fire–climate interactions. For example, in addition to emissions of CO_2 and other greenhouse gases, fires emit aerosols including black carbon that affect the efficiency of both atmospheric and surface absorption of solar energy, with resultant cooling and/or warming effects. These aerosol emissions are not well characterized or quantified, particularly across a range of vegetation and fuel types, fire environments, and fire intensity. New techniques for measurement, analysis, and modeling are required to help investigate their separate and combined roles as climate forcers. Many statistically-based climate–fire relationships and vegetation models have very limited ability to project future trends in wildfire, especially for 'mega-fires,' a term used to describe landscape-scale wildfires that occur under extreme fire weather conditions and exceed all efforts at direct control (Williams, 2013). While the strong relationships between atmospheric teleconnection/sea surface temperature (SST) patterns and wildfire activity are useful for seasonal forecasting applications, their application to climate change scenarios is problematic (Bonan, 2008). A gap will remain for some time in the future between the temporal coverage of weather forecast models and the temporal resolution of climate models (Fischer et al., 2013) However, promising improvements to climate models may result in better multi-year projections and predictions of interannual variability (Liu et al., 2014). Life-cycle accounting (e.g. fuel to emissions to deposition to sequestration) of climate relevant fire emissions will also contribute to more accurate long-term assessments of the potential for climate change mitigation by terrestrial vegetation (GOFC, 2009).

3. Significance and conclusions

Increasing public attention is focused on climate change as a driver of increased fire activity (e.g., fire size, severity, and annual area burned), but scientists and managers are only beginning to consider the role of fire emissions in the global carbon cycle and as a feedback to the climate system (van der Werf et al., 2008). Fire emissions are an important mechanism in the movement of sequestered carbon through wildland ecosystems into the atmosphere and other terrestrial and aquatic ecosystems. Increased high energy release fires predicted to occur with climate change may accelerate carbon cycling from the Earth's surface to the atmosphere (Goetz et al., 2007; Miller et al., 2008; Pechony and Shindell, 2010; Westerling et al., 2006). A 'new normal' for wildfire activity may be similar to the Biscuit fire (2002, southern Oregon and northern California) that emitted $\sim$20 Mg C ha^{-1}, representing $\sim$16 times the pre-fire annual net ecosystem production (Campbell et al., 2007). Global carbon cycle inversion model estimates have raised concern that increased forest disturbance may accelerate climate change through feedback loops that release large carbon sinks from unmanaged northern forests and significantly decrease the long-term carbon sequestration potential of those forests (Kurz et al., 2008). These changes in fire activity and emissions are occurring at a time when climate change policies are promoting enhanced forest-based carbon sequestration, and these directives will require appropriate fire and fuel management practices (including prescribed fire) to achieve such goals, where ecologically appropriate (Canadell and Raupach, 2008; Wiedinmyer and Hurteau, 2010). We recommend reading the eight following articles in this issue as they provide considerable additional insight into the issues discussed in this overview article.

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