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"Potential Climate Feedbacks of Changing Fire regimes in the U.S.: A Review"

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SUMMARY: The attached report fulfills the requirements of the interagency agreement to review the literature and prepare a review paper for publication in an appropriate scientific journal. After some additional editing and internal review, the paper will be submitted approximately 4 weeks from the date of this final report. The Joint Fire Sciences program will be kept informed of the progress of publishing this paper as it works through the review and publication process.

Climate feedbacks of fire burning and fire emissions in the US

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Abstract: Fire is a major ecosystem disturbance types that can profoundly impact vegetation dynamics, atmospheric gases and aerosol composition and climate, and the welfare of wildlife and human society. While climate is generally a critical driving factor shaping the occurrence, spreading, and emissions of ecosystem fires, fires can in return provide important feedbacks to climate. With a recent increasing trend in burned area and fire emissions, there is an urgent need to understand how fire burning and fire emissions can influence climate. Here we reviewed major mechanisms of fire feedbacks to climate. We then assessed the influences of recent decades' US fire burning and fire emissions on local, regional, and global climate. Our research found that average annual fire-emitted carbon dioxide (CO_2) in the US during the recent decades increased global radiative forcing by about 0.033 W m^{-2}. Contributions from other species of gases and aerosols, and from fire-changed land surface albedo and vegetation successional dynamics were also examined and discussed. The review highlights the importance of improved data streams of fire occurrences and fire emissions in meeting the need for further research and ecosystem fire management.

1. Introduction

Fire is a major type of land disturbance whose history is as long as that of terrestrial plants and can be observed in almost every terrestrial biome (Bowman *et al.*, 2009). Each year about 345-464 million hectare (Mha) (2.3%-3.1%) of the Earth's land is burned (Randerson *et al.*, 2012; Giglio *et al.*, 2013). Most ecosystem fires are wildfires; but human-set prescribed fires are also common (e.g., Pollet *and* Omi, 2002). In recent decades, there is an increasing trend for global burned area and fire emissions (Westerling *et al.*, 2006; Giglio *et al.*, 2013); and this increasing trend is projected to continue through the coming decades (Flannigan *et al.*, 2009; Littell *et al.*, 2010; Liu *et al.*, 2014; McKenzie *et al.*, 2014).

Ecosystem fires have profound biological and social consequences. They kill living plants and animals, release greenhouse gases (GHGs, mainly carbon dioxide but also other trace gases) and aerosols like particulate matter (PM), NO_x, and volatile organic compounds (VOC), fertilize soils, assist seed transportation, modify landscapes, drive ecosystem successional dynamics, and influence local, regional and global carbon cycles (van der Werf *et al.*, 2004; Bowman *et al.*, 2009; Giglio *et al.*, 2010; IPCC, 2013). For example, it is estimated that the carbon loss of terrestrial ecosystems to fire burning is about 1.9-2.5 Pg C yr^{-1} (van der Werf *et al.*, 2010; Randerson *et al.*, 2012), equivalent to 4% of global terrestrial net primary productivity (NPP) (van der Werf *et al.*, 2006; Zhao *and* Running, 2010). In some forest ecosystems, frequently returning fires or intense fires burn down closed forests and create open spaces for post-fire regeneration and following successional cycles (Lorimer *and* White, 2003). Many components of fire emissions, such as PM, SO_2, NO_x, and secondary products like O_3, are also major air pollutants which could adversely impact human health (Arora *and* Boer, 2005; Goldammer *et al.*, 2008). For example, post-harvest agriculture burning is regarded as one major cause for the increased $PM_{2.5}$ concentration (Xing *et al.*, 2013; Lyu *et al.*, 2015). Release of GHGs, aerosols, and O_3 from fires, along with fire-induced changes in surface albedo could also impose a significant impact on climate by altering biochemical and biophysical properties of the atmosphere (Van der Werf *et al.*, 2006; Randerson *et al.*, 2006; Bowman *et al.*, 2009).

Given its significant impacts on ecosystem structure and functions, as well as on the welfare of humans and wildlife, the increase of fire frequency, intensity, or burned area has increased interest in intensive studies on the ecology and climatology of ecosystem fires (e.g, Schimel *and* Baker, 2002; Bowman *et al.*, 2009; Marlon *et al.*, 2012; Liu *et al.*, 2014). In

particular, the interconnection between fires and climate has become a central research theme in current fire science research programs (Westerling *et al.*, 2006; Bowman *et al.*, 2009; Liu *et al.*, 2014). The critical role of climate on influencing the ignition, spreading, and suppression of wildland fires has been long recognized (Westerling *et al.*, 2006; Flannigan *et al.*, 2009). For example, the wet-drought cycles can coincide with the oscillation of fire activities − biomass accumulated during wet years provides fuels for large fires during dry years (Zeng *et al.*, 2014; Mondal *and* Sukumar, 2016). At large scales, high fire incidence in the tropics is typically observed during strong El Niño years (Van Der Werf *et al.*, 2004; Langmann *et al.*, 2009).

Despite the large volume of fire studies centering on climate, relatively few have investigated the climate consequences of fire disturbances. Most studies viewed climate as an independent factor that impacts the extent and intensity of fire burnings. However, the fire-climate interaction is not unidirectional. In recent decade, there is an increasing interest in treating fire and climate (and sometimes vegetation as well) as an interacting system (e.g., Trouet *et al.*, 2006; Liu *et al.*, 2014) in which fire also provides important feedbacks to climate. The feedback of fires to climate comes from two major categories of mechanisms − through fire emissions and fire induced landscape modification. In the first one, emissions of greenhouse gases and aerosols from fires can change atmospheric radiative forcing (Randerson *et al.*, 2006; Balshi *et al.*, 2009; Amiro *et al.*, 2010; IPCC, 2013), influence the reflectivity and absorption of incoming solar radiation, and modify atmospheric boundary-layer dynamics (Bowman *et al.*, 2009). In the second one, fire burning changes vegetation composition and dynamics, and consequently surface albedo (Van der Werf *et al.*, 2006). Current understanding of these feedback mechanisms is highly imbalanced. For instance, we now have some confidence about estimates

of radiation budget changes by CO_2 emissions from fires (IPCC, 2013). Yet we still know little about the impact of aerosol emissions on the radiation budget, since different aerosol species may impose a positive or negative effect (IPCC, 2013). The problem of aerosol feedback can be further complicated by the fact of poorly quantified aerosol emissions, whose species composition varies considerably across different vegetation and fuel types, climate, and fire intensity (IPCC, 2013). We know even less about the chemical interactions between different atmospheric layers and how these processes can be changed by different species or aerosols emitted from fires under different weather and radiative conditions (Bowman *et al.*, 2009). Hence there is a great demand for research to improve the measurement, analysis, and modelling of fire emissions and their climate impacts.

In the United States, wildland fires and prescribed fires are also of great concern among the research community, land managers, policy makers, and general public. A summary analysis of wildfire activity statistics of the US indicated that about on average 2.3-2.7 million hectares (Mha) of lands were burned each year over the contiguous US states during the last two decades (Wiedinmyer *and* Neff 2007; Short, 2014). In addition to widespread impacts on lives and property, the resulting carbon emissions from the US fires is estimated to be from 163-263 TgC yr^{-1} (Wiedinmyer *and* Neff, 2007), which is comparable to the net uptake of C from the atmosphere by forests in the US (USEPA, 2014). Analysis of wildfire occurrence also suggests an increase in annual burned area in the US over the last decades, despite substantial fire suppression efforts (USDA–USDI, 2000; WGA, 2000; NWCG, 2001). The widespread distribution of wildfires in the US and the associated large amount of fire emissions of GHGs and aerosols (Wiedinmyer *and* Neff, 2007; van der Werf *et al.*, 2010; Xing *et al.*, 2013; Larkin *et al.*, 2014) are likely to exert a significant impact on regional and global climate, which, however, is

poorly understood.

In this paper, we aim to assess the contribution of US prescribed fires and wildfires to atmospheric greenhouse gases and aerosols and their potential for changing radiative forcing and global climate. It will also include the effects of regional and larger scale atmospheric chemical processing of the fire emissions, surface albedo changes, and resulting influences on climate. We will first review the key mechanisms through which biomass burning feeds back to climate, including influences of particulate and ozone air pollutants and influences through modified land surface albedo and vegetation dynamics. Second, we will review burned area, fire emissions, fire-caused changes in landscape and vegetation dynamics in the US, and their influence on local, regional, and global climate. Finally we will identify important issues for modelling the influence of changing fire regimes on climate change, including research need on mechanistic studies, fire occurrence data streams, and methodologies to generate national emissions inventories.

2. How fire and fire emissions impact climate – a review of major mechanisms

Figure 1 provides a schematic overview of the major mechanisms that determine climate feedbacks of fires. Gases and particles emitted from fires, including both primary and secondary products, can exert impacts on radiative budgets (Ward *et al.*, 2012), change clouds and precipitation (Bowman *et al.*, 2009), and modify atmospheric chemistry and influence atmospheric boundary processes (Daskalakis *et al.*, 2015; Veira *et al.*, 2015a) (Fig. 1). Additionally, fires can trigger land cover changes and ecosystem dynamics which can also affect the atmosphere through heat, water, and momentum exchanges (Fig. 1).

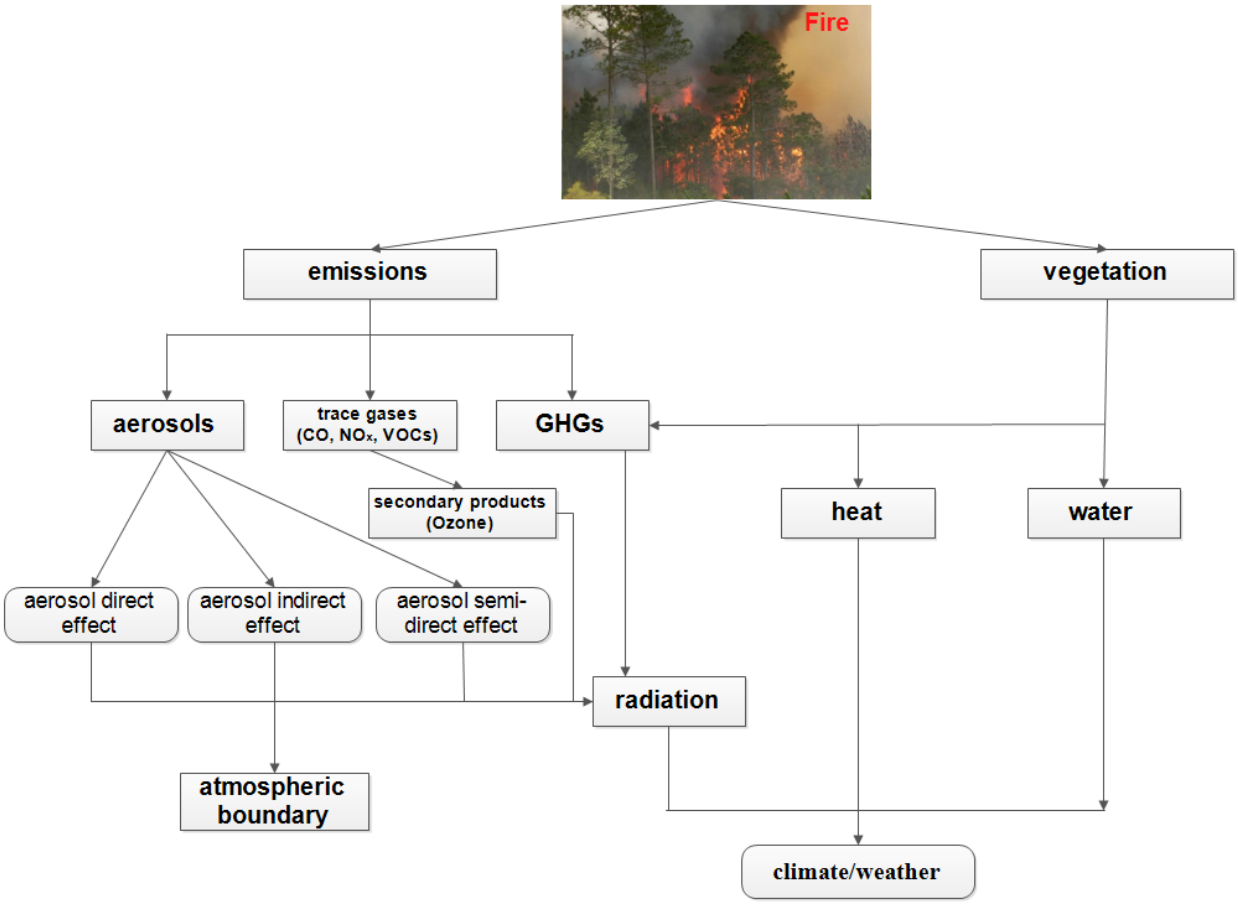

Figure 1 Schematic diagram of climate feedbacks of fires and fire emissions.

2.1 Fire emission induced radiative forcing changes

The primary feedbacks of fire to climate come from their impact on radiative forcing (Fig. 2). Biomass burning produces greenhouse gases, primarily CO_2, that results in a positive radiative forcing. Fires emit carbonaceous and other aerosols, which influence climate through direct and indirect radiative effects (Ward *et al.*, 2012). In addition, aerosols can impact global oxidative capacity through heterogeneous processes and photolysis, leading to further changes in radiative forcing via CH_4 (Mao *et al.*, 2013a). Fires are also one of the largest uncontrollable sources of trace gases, and profoundly influence regional/global atmospheric composition and radiative forcing. The trace gas emissions from fires react to produce ozone, a major greenhouse gas and

air pollutant, through the photochemical oxidation of carbon monoxide (CO) and hydrocarbons in the presence of nitrogen oxide (NO_x) (Mauzerall *et al.*, 1998). Meanwhile, emitted CO and hydrocarbons provide additional sinks for OH, extending the lifetime of methane (CH_4). By considering the radiative forcing of gas and aerosol species other than GHGs, the sign and magnitude of radiative forcing due to biomass burning emissions as a whole is not well quantified (Fig. 2), although several recent studies suggest a possible warming effect (Mao *et al.*, 2013b; Jacobson, 2014).

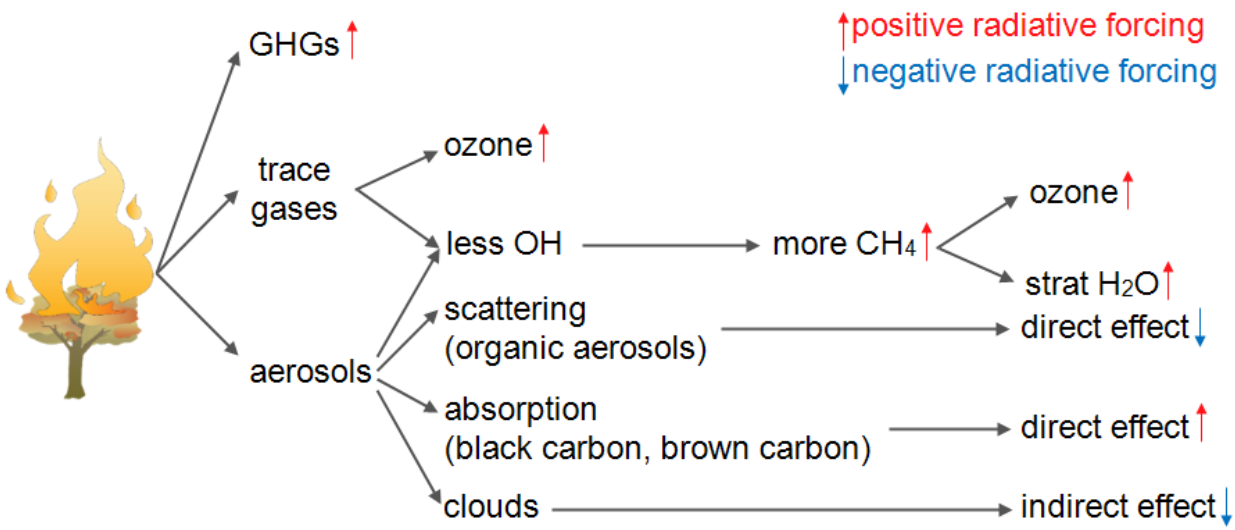

Figure 2 Schematic diagram of the multiple impacts of biomass burning emissions on radiative forcing.

2.1.1 Changes in radiative forcing by burning produced GHGs

Biomass burning emits several key GHGs, including CO_2, methane (CH_4), and nitrous oxide (N_2O). Among them, CO_2 is the dominant fraction of fire emissions (Andreae *and* Merlet, 2001). Globally, biomass burning causes a total carbon loss of 2.0 Pg C per year, equivalent to

about 19% of all fossil fuel emissions (Bowman *et al.*, 2009; Giglio *et al.*, 2010). The majority of the fire-released C to the atmosphere is in the form of CO_2 (Urbanski *et al.*, 2008). This large amount of CO_2 and other GHG emissions by biomass burning imposes a significant and positive contribution to the radiation budget. For instance, climate model simulations show that fire-caused increase in atmospheric CO_2 concentration generates a radiative forcing of 0.83 W m^{-2} (Ward *et al.*, 2012), equivalent to about 50% of the radiative forcing by the total pre-industrial CO_2 emissions (Stocker *et al.*, 2013). Furthermore, fire-induced increase in atmospheric CH_4 and N_2O contribute about 0.04-0.09 W m^{-2}, and 0.03-0.04 W m^{-2} to the global radiative forcing, respectively (Ward *et al.*, 2012). Although biomass burning does not directly emit ozone (O_3), burning-produced reactive oxygenated compounds promote the production of ozone, which results in a positive radiative forcing of ~0.15 W m^{-2} globally (Fig. 2, Bowman *et al.*, 2009).

2.1.2 Changes in radiative forcing by fire-emitted aerosols

Biomass burning is also one of the largest sources of atmospheric aerosols (Bowman *et al.*, 2009). The global emission of burning-induced black carbon is about 2.2 Tg C per year (van der Werf *et al.*, 2004, 2006, 2010; Randerson *et al.*, 2005; Wiedinmyer *et al.*, 2011), which is about 40% of total black carbon emissions. While the impact of fire-emitted GHGs on radiative forcing has been well investigated both qualitatively and quantitatively, the impact of fire-induced aerosols on climate is more complex. Fire-produced aerosols can influence radiative forcing through three mechanisms, including “aerosol direct effect”, “aerosol indirect effect” and “aerosol semi-direct effect” (IPCC, 2007, 2013; Liu *et al.*, 2014).

Firstly, aerosol emissions can contribute directly to the radiation budget by scattering light

(negative radiative forcing) and absorbing solar radiation (positive radiative forcing). This mechanism is known as “aerosol direct effect” (IPCC, 2013). The radiative forcing from the aerosol direct effect is relatively weak, with a magnitude of 0.0±0.20 W m^{-2} globally (IPCC, 2013), and is also highly uncertain. Aerosols emitted from biomass burning include black carbon (BC) and organic carbon (OC), which have different radiation absorption characteristics (Menon *et al.*, 2002).

Black carbon, which is produced from the incomplete combustion of biomass and fossil fuel carbon, makes up about 5–10% of fire-emitted aerosols. Globally about 40% of total BC emissions are caused by forest and savanna burning (Ramanathan *and* Carmichael, 2008). Black carbon is the most strongly light-absorbing aerosol component and is capable of trapping both incoming and outgoing radiation of all wavelengths, resulting in a surface warming effect (IPCC, 2007). Ramanathan *and* Carmichael (2008) estimated that the radiative forcing of total BC emissions can warm the earth surface by about 0.5-1.0 °C.

Fire-emitted organic carbon, also known as brown carbon, makes up about 50-60% of fire aerosols, compared to 5-10% for black carbon. However, the radiation absorbing capacity of OC has not been accounted for in most IPCC climate models. In contrast to BC, which absorbs at all visible wavelengths (Bond *and* Bergstrom, 2006), OC shows strong absorptivity at short visible and ultraviolet wavelengths. Biomass burning is considered one of the major sources for OC, including both primary emissions and secondary formation of humic-like substances (HULIS) (Laskin *et al.*, 2015). In fact, recent measurements suggest that biomass burning may be the dominant source of OC over the US (Washenfelder *et al.*, 2015). Several studies suggest that OC may impose a strong warming effect at the top of the atmosphere (0.04-0.57 Wm^{-2}), comparable

to that from BC (Arola *et al.*, 2011; Chung *et al.*, 2012; Kirchstetter *and* Thatcher, 2012; Feng *et al.*, 2013; Lin *et al.*, 2014; Wang *et al.*, 2014; Saleh *et al.*, 2015).

Secondly, fire aerosol emissions can also impact clouds, which is known as "aerosol indirect effect" (IPCC, 2013). Aerosols, serving as cloud condensation nuclei (cloud seeds, or CCNs), microphysically modify cloud droplet concentration, cloud droplet size, and liquid water content held fixed ("cloud albedo effect"), and has an impact on liquid water content, cloud height and lifetime of clouds ("cloud lifetime effect") (IPCC, 2013). A recent model-based study suggests that the radiative forcing from the aerosol indirect effect is about -1.6 W m^{-2} (Ward *et al.*, 2012), much larger than that of the aerosol direct effect. However, as there are huge uncertainties in the cloud simulation in models (IPCC, 2013), this estimated aerosol indirect effect on global radiation budget is also of great uncertainty.

Thirdly, both direct and indirect aerosol radiative forcing introduce a change in water and energy exchanges between land and atmosphere, and could thus modify atmospheric structure. Such changes can feedback to atmospheric water vapor and clouds, and influence incoming solar radiation. This is known as "aerosol semi-direct effect" (IPCC, 2007). However, currently no study has quantified the radiative forcing from the burning-induced aerosol semi-direct effect.

In addition to the impacts on atmospheric radiation, some of the fire-emitted aerosols will re-deposit on the land surface and interact with surface processes, which may have a local impact on surface albedo and climate. In particular, the deposition of black carbon on snow-covered surfaces can reduce surface albedo and increase surface radiation absorption, which help melt

snow and contribute to climate dynamics (Hadley *and* Kirchstetter, 2012). The role of fire-emitted BC-snow interaction is particularly significant in boreal regions where boreal fires contribute more than half of the total BC deposition (Ramanathan *and* Carmichael, 2008; Hadley *and* Kirchstetter, 2012; IPCC, 2013). The change in forcing caused by the deposition of fire-emitted BC is estimated to be about 0.60 W m^{-2} (Ramanathan *and* Carmichael, 2008; IPCC, 2007, 2013).

2.2 Fire induced atmospheric secondary products

Fire emissions also impact climate via their interactions with existing atmospheric chemicals that can create secondary atmospheric products, and through their modification of atmospheric boundary conditions. The best known secondary product induced by fire is O_3 in the troposphere, which is produced from CH_4, CO and NO in photochemical reactions (Bowman *et al.*, 2009). However, the estimate of chemical transformation and ozone production from wildfire emissions is highly uncertain. Field observations show large variations in the ozone production in wildfire plumes across the world (Jaffe *and* Wigder, 2012; Akagi *et al.*, 2013; Voulgarakis *and* Field, 2015). Many studies use dO_3/dCO as an indicator of ozone production from fire plumes, and they find this ratio varying from -0.1 to 0.9 among different studies (Jaffe *and* Wigder, 2012). Some fire plumes show significant enhancement of ozone in fire plumes (Pfister *et al.*, 2006; Val Martín *et al.*, 2006; Yokelson *et al.*, 2009), while others show very little ozone formation (Alvarado *et al.*, 2010; Zhang *et al.*, 2014). This is in part due to the large variability of fuel burned and burning conditions of wildfires, and in part due to the complex emissions and photochemistry in fire plumes, which is poorly quantified in current models. Poor characterization of ozone production from fire plumes largely impedes our capabilities for

assessing the impact of wildfires on air quality and radiative forcing.

One major issue in quantifying ozone production from fires is the largely unaccounted oxygenated volatile organic compounds (OVOCs) from fire plumes. Several studies indicate that OVOCs are abundantly emitted from wildfires (Karl *et al.*, 2007; Akagi *et al.*, 2011; Warneke *et al.*, 2011; Yokelson *et al.*, 2013), but most of these emissions have not been estimated in previous emission inventories (Andreae *and* Merlet, 2001). In fact, a very recent study suggests that OVOCs account for 60-70% of VOC mass emitted from wildfire plumes (Gilman *et al.*, 2015). It is likely that these OVOCs may lead to the rapid production of Peroxyacetyl nitrate (PAN) and other organic nitrates (Akagi *et al.*, 2012; Jaffe *et al.*, 2013), largely suppressing ozone production from fire plumes locally. These organic nitrates may be transported and oxidized downstream, returning NO_x and promoting ozone production in remote regions (Jacob *et al.*, 1992). Further, these OVOCs can be photolyzed (such as aldehydes) and serve as additional sources of HO_x radicals, further enhancing ozone production. On the other hand, these unaccounted OVOCs may be oxidized to form secondary organic aerosols (Alvarado *et al.*, 2015a), which may impact particulate matter (PM) air quality. Characterization of OVOCs and their evolution in fire plumes is essential to assess the impact of fire emissions on regional and global air quality and climate.

Another issue concerns the representation of fire plumes in global and regional models. First, the injection heights for fire plumes remain largely uncertain (Alvarado *et al.*, 2010; Val Martin *et al.*, 2010, 2012; Turquety *et al.*, 2007; Veira *et al.*, 2015b). The injection of fire plumes into surface layer, convective boundary layer or free troposphere, will lead to large differences in its subsequent transport, photochemistry and global abundance of trace gases and particles (Veira

et al., 2015a; Daskalakis *et al.*, 2015). Second, automatic dilution of fire plumes into large grid boxes may lead to large bias in simulating the chemical evolution of fire plumes (Alvarado *et al.*, 2009). For example, heterogeneous chemistry may play a major role in the radical budget and NO_y partitioning due to high concentrations of trace gases and particles, but its role may be largely diminished when the fire plume is instantaneously diluted into grid boxes. Third, the chemistry of fire plumes may be in a very different NO_x regime than ambient air, and it is poorly examined in the past (Alvarado *et al.*, 2015b). Estimating ozone production from fire plumes remains a big challenge, leading to large uncertainties in quantifying its impact on air quality and radiative forcing.

2.3 Fire induced changes in landscape and surface albedo

In addition to feeding back to climate through their influence on the gas and particle matter composition of the atmosphere, fires can also impact climate via land surface processes, in particular as the result of altered surface albedo (Randerson *et al.*, 2006; Bowman *et al.*, 2009). Surface albedo decreases rapidly after burning, but may be followed by an increase due to a larger exposure of snow and/or an increasing brighter pastures and croplands over a longer period (Bowman *et al.*, 2009). The change in surface albedo can cause a biophysical feedback to the climate. Within a short post-burning period, decreasing albedo leads to short-lived warming as the dark-surface absorbs more solar radiation (Jin *and* Roy, 2005). Its magnitude could be strong enough to cancel the negative forcing of burning-produced aerosols (Randerson *et al.*, 2006). However, over a longer post-burning period, surface albedo may increase from the interaction with snow coverage and the vegetation succession. In high latitudes, the reduced canopy coverage by burning is likely to be replaced by snow coverage, which has a much higher surface albedo than dark forest. In temperate and tropical regions, pastures and croplands that are much

lighter than dark forest may take over the burned areas, also resulting in increasing albedo (Jin *and* Roy, 2005). Overall, fire-induced surface albedo change is estimate to result in a negative forcing of -0.15 W m^{-2} (Van der Werf *et al.*, 2006).

Furthermore, fires initialize vegetation successional dynamics, which have profound implications for local and regional carbon and water cycles. Changes in carbon and water cycles are known to affect local, regional, and global climate and weather (IPCC, 2013).

2.4 Short- and long-term climate impacts of fire burnings

The climate impacts of fires and fire emissions can last for short or long time periods; and can be confined to a limited area or extend to a larger region or the entire globe through regional and global atmosphere circulations (Bownman *et al.*, 2009). The short- and long-term climate impacts of fire burning significantly differ from each other (Bownman *et al.*, 2009; Hurteau *and* Brooks, 2011; Marlon *et al.*, 2012). While short-term climate impacts could be extremely significant, long-term climate impacts could be less significant owing to vegetation regrowth of burned areas. Furthermore, biomass burning might induce a cooling effect within a short period, but a global warming effect on long term (Jacobson, 2004). The long-term climate impact of fire burning can be further complicated with the fire-induced surface albedo effect. For example, boreal forest fire is estimated to induce a significant positive radiative forcing during the first year (34 W m^{-2}), but a negative radiative when averaged over a fire cycle (80 years, -2.3 W m^{-2}) (Randerson *et al.*, 2006).

Fire burn area and intensity also vary largely from year to year. As a result, biomass burning has become a driving factor of interannual variability of atmospheric carbon dioxide and

methane (van der Werf *et al.*, 2004; Bowman *et al.*, 2009; Langmann *et al.*, 2009; Arneth *et al.*, 2010). And the observed anomalous in CO_2 concentration could be well explained by the huge emission of these gases caused by burning in high fire activity years (Schimel *and* Baker, 2002). For example, biomass burning explains about 2/3 of the interannual variability in the CO_2 growth rate during 1997-2001 (Bowman *et al.*, 2009). The large increase in atmospheric CO_2 in 1997 is substantially attributed to the carbon emission from fires in Indonesia in 1997 (810-2570 Tg C) (Langmann *et al.*, 2009). Therefore, radiative forcing by burning-caused GHGs can also show a large interannual variation.

2.5 Local and regional climate impacts of fires

Most fires are local and do not last for long. Therefore burning-induced particles are not always transported in the atmosphere for a long distance. As a result, the climate impacts of most individual fires are usually spatially confined, except for the climate impact of burning induced greenhouse gases. For example, fires can lead to regional warming or regional cooling through emissions of aerosols, hinging upon aerosol composition, planetary albedo and clouds (Randerson *et al.*, 2006). Fires directly regulate surface energy balance by changing surface albedo, and thus change local climate. Fires can also decrease local precipitation by reducing vertical convection and limiting rain-cloud formation (Bownman *et al.*, 2009).

3. Fire feedbacks to climate in the US

As we reviewed in Section 2, the feedbacks of fires to climate come from (1) the extent of landscapes affected by fires and the intensity of burns, and (2) quantity of gases and aerosols emitted (Fig. 1). Both landscape changes and fire emissions can induce a variety of climate feedback mechanisms, including effects on albedo, radiative forcing, energy, water, and

momentum exchanges between land and atmosphere (Fig. 1). Therefore, a quantitative assessment of the feedback of US ecosystem fires to climate will first require data streams of burned areas and associated emissions. In this section, we will first review current available data sets and studies on burned areas and emissions of US ecosystem fires. Then we will investigate how these data sets can be used for a quantitative assessment of the climate feedback from US ecosystem fires.

3.1 Data sets of burned area and fire emissions

3.1.1 Burned area

Nearly one century of wildfire monitoring and research has left a wealth of wildfire activity data for researchers and land managers (Short, 2015). Available data sets of burned area are usually acquired from two sources – ground observations (bottom-up approach), and satellite products (top-down approach). In the early years, the bottom-up approach was the only available information for monitoring wildfire activities, in which incident-level wildfires were reported and documented by various government agencies or organizations (e.g., Kolden *and* Brown, 2010; Thomas *and* Butry, 2012; Short, 2014). In more recent decades, remote-sensing tools have been increasingly used in recording and analyzing wildfire activities (e.g, Giglio *et al.*, 2010; van der Werf *et al.*, 2010). In particular, algorithms to extract fire information from satellite imagery have grown rapidly and resulted in several satellite products of burned area with different spatial and temporal scales. Short (2015) provided a detailed overview on the available US wildfire activity data sets and their uncertainties and biases. Table 1 lists currently available US fire data sets.

Table 1. List of currently available US fire data sets.

Short name	NICC	MTBS	FPA-FOD	GFED
Long name	National Interagency Coordination Center	Monitoring Trends in Burn Severity	Fire Program Analysis fire-occurrence database	Global Fire Emissions Database
source	https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html	http://www.fs.usda.gov/rds/archive/Product/RDS-2013-0009	http://www.mtbs.gov/nationalregional/burnedarea.html	http://www.globalfiredata.org
Period	1960-2015	1984-2014	1992-2009	1997-2014
Region	US	US	US	Global
Method	fire records based	Satellite imageries based	fire records based	Satellite imageries based

The documentation of fire activities in the US can be tracked back to the early 20th century (Short, 2015). Individual fire incidence is recorded by different US government agencies and organizations, including the USFS, the US Bureau of Land Management (US BLM), state and local land management and fire authorities (Short, 2015). Fire activity statistics at federal, regional and state levels are published and analyzed based on these records. The "Smokey Bear Reports" published by the USFS is one of the most cited fire statistics which summarize wildfire activities by US state. The National Interagency Coordination Center (NICC) also provides reports on national, regional, and state wildfire activities of recent decades (e.g., Reid *et al.*, 2004; Andrews, 2005; Hammer *et al.*, 2009; Urbanski *et al.*, 2009; Kolden *and* Brown, 2010; Thomas *and* Butry, 2012). One of the most complete and publicly available database of US fire activities is the Fire Program Analysis Fire-Occurrence Database (FPA-FOD) compiled by the USFS based on available fire information from different authorities (Short, 2014). The FPA-FOD includes about 1.6 million fire records, spanning the period of 1992-2011. The spatial resolution of the FPA-FOD is not unified, but at least <2.6 km^2, which allows moderate-resolution spatial analyses (Short, 2014).

Remotely sensed fire data are growing in recent decades. Data of burn scars have been derived from numerous satellite sensors, including Landsat, the Moderate Resolution Imaging Spectroradiometer (MODIS), the Geostationary Operational Environmental Satellite (GOES) system and the Visible Infrared Imaging Radiometer Suite (VIIRS) (e.g., Eidenshink *et al.*, 2007; Hawbaker *et al.*, 2008; Giglio *et al.*, 2010; Urbanski *et al.*, 2011). For example, based on Landsat imageries, the Monitoring Trends in Burn Severity (MTBS) product (Eidenshink *et al.*, 2007) provides data of large (>0.4 ha) fire burn scars that are frequently used in the research of large-fires in the US back to early 1980s (Riley *et al.*, 2013; Dennison *et al.*, 2014). Various fire

products derived from the MODIS are also widely used for fire-related studies in the US and globally (Giglio *et al.*, 2010; Urbanski *et al.*, 2011; Hawbaker *et al.* 2013; Mouillot *et al.* 2014; Parks, 2014; Schroeder *et al.*, 2014). Among them, the Global Fire Emissions Database (GFED) is perhaps the most popular one. GFED provides information of burned area at high temporal (daily) and spatial (500m) resolutions from 2000 through the present based on a MODIS direct broadcast BA algorithm (MCD64A1) and active fire detections (Giglio *et al.*, 2010, van der Werf *et al.*, 2010). Monthly burned area at the resolution of 0.5 degree latitude by longitude, which is aggregated from daily information, can track back to 1997 (Giglio *et al.*, 2010).

Recently, airborne active fire imaging is also available for some local scale monitoring and research studies (e.g., Ambrosia *et al.*, 2011). However, so far airborne fire products are rarely used in regional or continental fire analyses due to their limited coverage.

3.1.2 Fire emission inventories

CO_2 is the largest component of fire emissions that have significant feedback to climate. Quantification of CO_2 emission is based on area burned, fire severity, and fuel amount. Currently there are four major inventory databases of fire emissions for the US: the EPA National Emissions Inventory (NEI, Raffuse *et al.*, 2012), the Fire INventory NCAR (FINN, Wiedinmyer *et al.*, 2011), the Global Fire Emissions Database (GFED, van der Werf *et al.*, 2010), and the EPA greenhouse gas emissions reports. The sources of data and emission estimation methods are different among these data sets (Table 2; Larkin *et al.*, 2014).

Table 2. List of currently available inventories of wildfire induced emissions. (Source: Larkin *et al.*, 2014)

Short name	GFED	FINN	NEI	EPA GHG
Long name	Global Fire Emissions Database	Fire INventory NCAR	EPA National Emissions Inventory	US EPA Greenhouse Gas Inventory
Reference	van der Werf *et al.*, 2010	Wiedinmyer *et al.*, 2011	Raffuse *et al.*, 2012	US Environmental Protection Agency, 2012
Source	http://www.globalfiredata.org/Data/index.html	http://bai.acd.ucar.edu/Data/fire	http://airfire.org/data/emissions	A final report of US Environmental Protection Agency
Area burned	MODIS burn scar method. Active fire detects through regression trees	MODIS active detects scaled by land cover type and percent bare cover	NOAA HMS (includes MODIS, AVHRR, GOES active detects). MTBS perimeters. Incident reports	NIFC wildland fire statistics scaled by (forested area/area under fire protection)
Available fuel	Carnegie-Ames-Stanford-Approach (CASA) biogeochemical model	MODIS land cover lookup table	LANDSAT derived map of FCCS fuel beds	Forest carbon density from FIA (includes aboveground biomass, dead wood, litter)
Consumption fraction	Lookup table fraction of fuel type scaled by soil moisture	Function of % tree cover	Calculated by consume fuelbed consumption model	0.45 (from IPCC methodology)
Emissions factors	Based on latest updates of Andreae *and* Merlet, 2001	Primarily from Akagi *et al.*, 2011	Calculated by FEPS emissions model	Based on IPCC methodology

Among these data sets, FINN and GFED have been used in global and regional fire emission studies (e.g., Larkin *et al.*, 2014); while the NEI and the EPA GHGs Report are official inventories including emissions from all sources and other gases besides CO_2. Some also include N_2O, fine scale particulate matter ($PM_{2.5}$), and black carbon (BC). In addition, when using these inventories, one needs to consider the associated uncertainties as a result of problems during data acquisition and processing (e.g., van der Werf *et al.*, 2010; Wiedinmyer *et al.*, 2011; Raffuse *et al.*, 2012). For example, wildfires are highly seasonal and also heterogeneous across different regions (Bowman *et al.*, 2009; Langmann *et al.*, 2009), resulting in high spatial and temporal variability in fire emissions which can make the development of fire emission inventories very difficult.

3.2 Annual burned area in the US

Figure 3 shows the changes in US burned area from 1960s to present, according to data sets from NICC, FPA-FOD, MTBS, and GFED. There are significant differences among different data sets for the estimate of US annual burned area (Fig. 3), which ranges between 0.3-4.3 Mha per year. Other research showed similar figure of annual burned area. For example, studies based on NICC statistics during 1998-2011 suggested that wildfires affect about 2.7 Mha of land annually, and between 1.5-2.8 Mha yr^{-1} during 2001-2004 (Short, 2014). Leenhouts (1998) found that during 1987-1996, annual burned area from wildland fires, prescribed fires, and agriculture fires range between 0.4-2.2, 1.2-2.0, and 2.9-3.2 Mha, respectively.

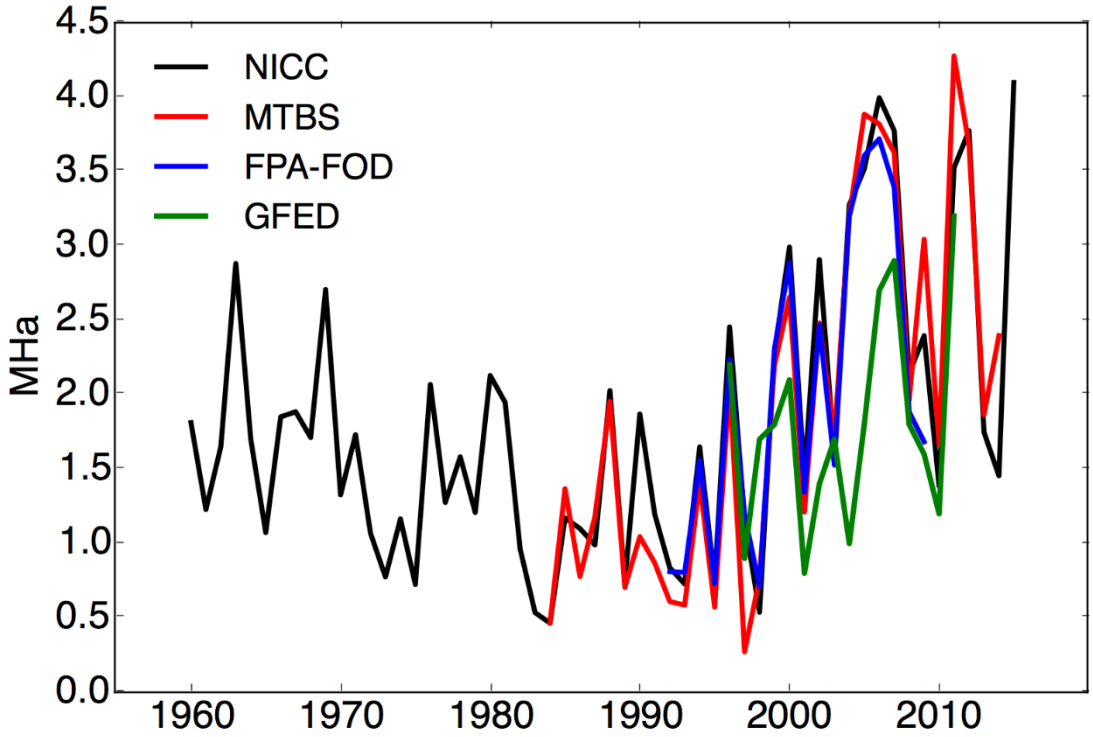

Figure 3. The changes in US burned area from 1960s to present, according to data sets from National Interagency Coordination Center (NICC), Fire Program Analysis fire-occurrence database (FPA-FOD), Monitoring Trends in Burn Severity (MTBS), and Global Fire Emissions Database (GFED).

While different data sets show a wide range in annual burned area, they all suggest an increasing temporal trend in fire burned area since ~1990 (Fig. 3). This increase in fire burned area agrees with many previous studies (e.g., Westerling *et al.*, 2006; Bowman *et al.*, 2009; Short *et al.*, 2014). In particular, Littell *et al.*, (2016) found that along with increased drought severity, the number of fires and area burned have significantly increased in the southwestern US, and western mountain regions. The increase rate of total burned area in the US during the last two decades was over 3×10^4 ha per year (Dennison *et al.*, 2014).

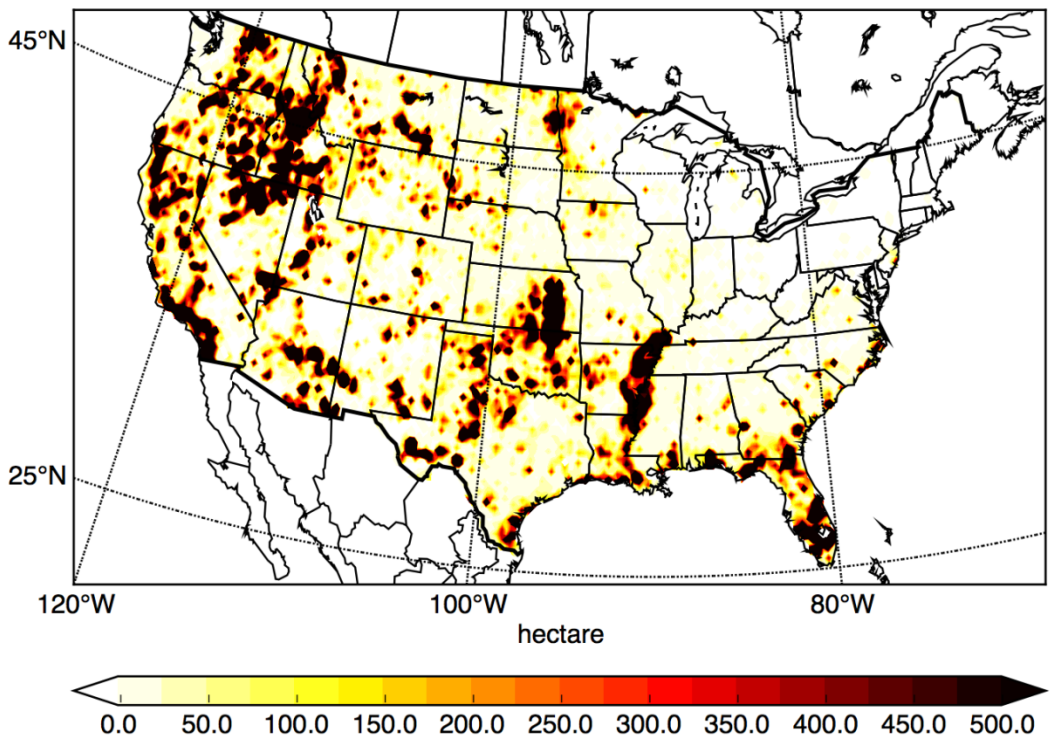

Figure 4. Spatial distribution of US burned area in each grid (0.25° latitude by 0.25° longitude) derived from GFED data sets.

The spatial distribution of burned areas shows significantly more fire occurrences toward the western and the southeastern US, and much more limited occurrences in the northeastern and southeastern US (Fig. 4). The frequency of large fires is also higher in the western and eastern US. California, Oregon, and Montana are among the states with the largest burned areas. Climate and human activities are the main factors in shaping this spatial pattern of fires. In particular, the dry climate and dense forests, shrubs and grasslands in the western US contribute to the large burned scars frequently found there. In the Midwest plains, agriculture fires are more prevalent

(Wiedinmyer *et al.*, 2011; Short, 2014).

3.3 CO_2 emission in the US and its climate influence

The total global carbon emission from fires is about 2.0 Pg C per year, which equals about 22% of the global fossil fuel carbon emissions (van der Werf *et al.*, 2010). Fig.5 shows the US share of the global fire-emitted carbon from GFED, which is about 18Tg C per year for the period of 1997-2015. Wiedinmyer *and* Neff (2007) provided a much higher estimate of 79.9 Tg C per year (58.1±13.6 Tg C per year over the lower 48 states (CONUS) and 21.8±24.3 Tg per year in Alaska) during the recent years (2002-2006), roughly 4% of the global carbon emission from fires.

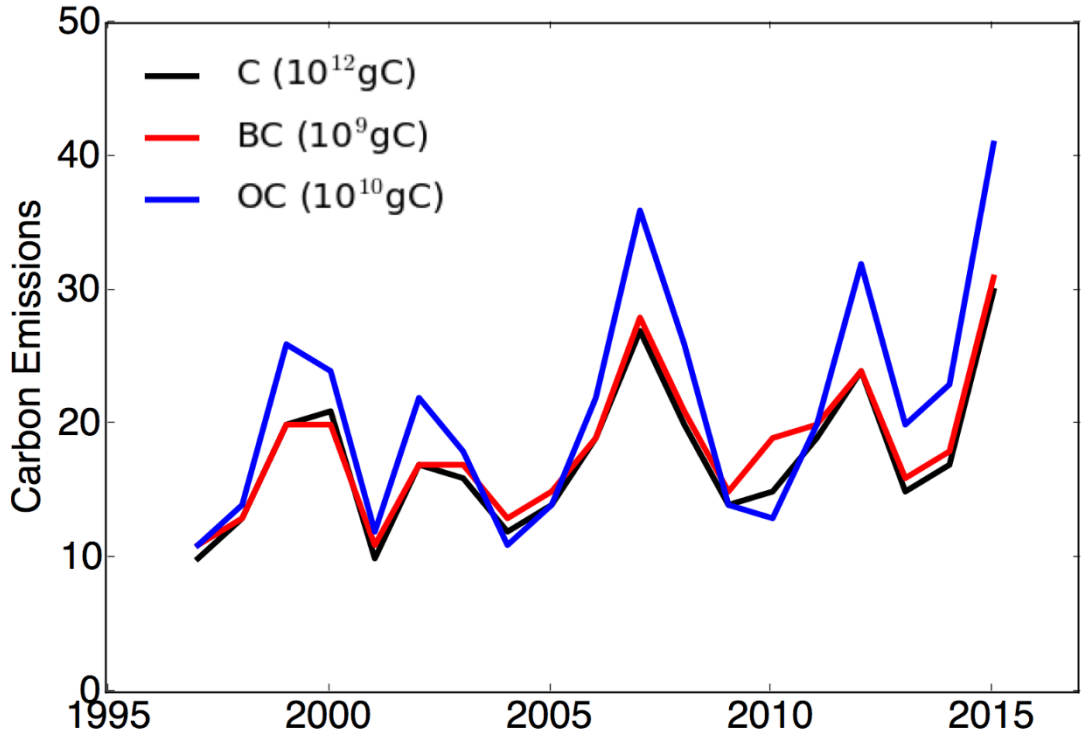

Figure 5. Changes in US fire carbon (Total carbon (C), black carbon (BC), organic carbon (OC)) emissions from GFED data sets.

The southeastern and the western US are the biggest contributors to the US fire CO_2 emissions from the conterminous US (Wiedinmyer *and* Neff, 2007) (Fig. 6). In total, fire caused CO_2 emissions are about 10 Tg C in the southeastern and western states (including Alabama, Florida, Georgia, Louisiana, and Washington). The dominant causes of fires are different among these two regions. Fires in the western US are dominated by lightening- and human-caused wildfires, while fires in the southeastern US by controlled agriculture and forest burnings. Fire caused CO_2 emission is very small in the northeastern and the midwestern states (e.g., <0.01 Tg C per year for Vermont or Rhode Island).

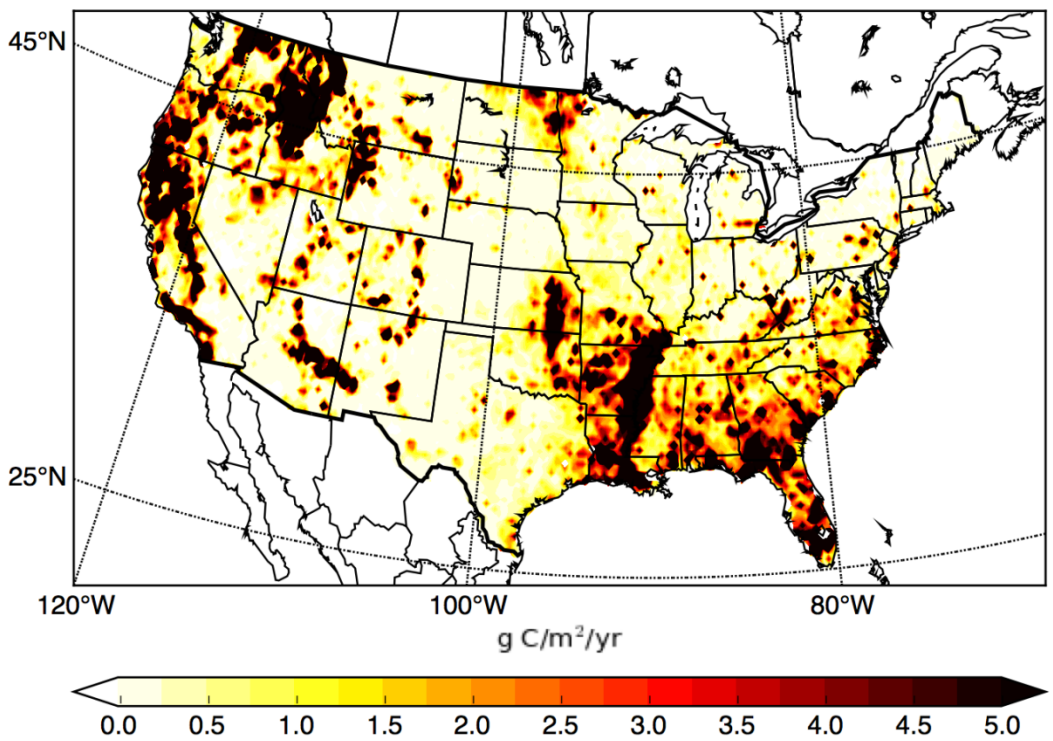

Figure 6. Spatial distribution of changes in US fire carbon emissions from GFED data sets.

According to a fire emissions inventory of 2006, about 86% of the carbon emissions in the western and the southeastern US came from needle-leaf forests (Wiedinmyer *and* Neff, 2007), suggesting that fire emissions from needle-leaf forests are the most dominant source of fire carbon emissions over the US Overall, needle-leaf forests emitted 78% of the fire carbon emissions over the CONUS. Carbon emissions from grassland and cropland burnings account for 5% and 3% of the nation's total carbon emission from fires (Wiedinmyer *and* Neff, 2007).

The relative contribution of carbon emissions from fires to regional carbon emission budgets changes seasonally and annually. In general, fire-caused monthly carbon emissions in the US show two peaks-the first peak often appears during the spring (March and April) and the second one during the summer (Wiedinmyer *and* Neff, 2007). The summer peak is usually bigger than the spring one (Wiedinmyer *and* Neff, 2007). In addition to the seasonality, the interannual variability of annual fire emissions over US is also quite considerable, due to randomly occurring large fires. High carbon emissions from fires are closely associated with drought; thus, climatic variability is a major driver of the high interannual and spatial variability in fire emissions (Schoennagel *et al.*, 2007). In addition, land management practices using fires can also explain some of the seasonally high fire carbon emissions as well (Wiedinmyer *and* Neff, 2007).

Climate model simulations show that globally, fire-caused increase in atmospheric CO_2 induces a radiative forcing of 0.83 W m^{-2} (Ward *et al.*, 2012), contributing about 50% of the radiative forcing by total CO_2 emissions relative to preindustrial conditions (IPCC, 2013). Considering the long residual time and high global dispersal capacity of CO_2 in the atmosphere, the annual 79.9 Tg C (or 293 Tg CO_2) released to the atmosphere solely by US ecosystem fires

heats the Earth by 0.033 W m^{-2}.

In addition to the radiative forcing by CO_2 emissions, fire-caused increases in other GHGs also increases radiative forcing globally by 0.04 ~ 0.09 W m^{-2} for CH_4 and 0.03 ~ 0.04 W m^{-2} for N_2O, respectively (Ward *et al.*, 2012). US ecosystem fires also contribute about 4% to that radiative forcing change. Biomass burning does not directly emit O_3, but fire-caused reactive oxygenated compounds promote the production of ozone, which results in a positive radiative forcing of ~0.15 W m^{-2} globally (Bowman *et al.*, 2009).

3.4 Fire aerosol emissions in the US and their contribution to climate

Fire aerosol emissions include fine particulate matter (<2.5 microns, $PM_{2.5}$), black carbon, brown carbon, carbon monoxide (CO), and other trace gases. Larkin *et al.*, (2014) examined three aerosol emissions inventories for the contiguous United Sates: the United States Environmental Protection Agency National Emissions Inventory (NEI), the Global Fire Emissions Database (GFED), and the Fire INventory NCAR (FINN). These three emissions inventories strongly differ from each other. For example, multiyear average PM2.5 emission from fires in US is estimated as 0.2 Tg yr^{-1} by the GFED and the FINN, but 1.7 Tg yr^{-1} by the NEI (Larkin *et al.*, 2014). NO_x emission is estimated as about 0.2 Tg yr^{-1} by the FINN and the NEI, but 0.1 by the GFED. In addition, the multiyear average black carbon emission induced by fire in US is estimated as 0.01 Tg yr^{-1} by the GFED, 0.02 Tg yr^{-1} by the FINN, and 0.10 Tg yr^{-1} by the NEI (Larkin *et al.*, 2014). Xing *et al.*, (2013) applied an activity data based approach to develop a consistent series of spatially resolved aerosol emissions in the US from 1990 to 2010. They found that forest fires account for 7% and 17% of the total PM_{10} (particulate matter <10 microns) and $PM_{2.5}$ in the US, respectively. A model-based estimate of fire aerosol emissions in the US gave values of 2.7 Tg

yr^{-1} for PM_{10}, 2.4 Tg yr^{-1} for $PM_{2.5}$, 1.3 Tg yr^{-1} for VOC, 0.68 Tg yr^{-1} for NO_x, 0.19 Tg yr^{-1} for NH_3, and 0.16 Tg yr^{-1} for SO_2 (Wiedinmyer *et al.*, 2006).

The observed interannual variability of total carbonaceous aerosol concentrations in the US is largely driven by summer wildfires, which emitted 0.26 μg C m^{-3} in the west and 0.14 μg C m^{-3} in the east (Park *et al.*, 2007). Non-summer wildfires and prescribed burnings contribute 0.27 and 0.31μg C m^{-3} of total carbonaceous aerosol concentrations in the west and east, respectively. The emission in the southeast is mainly contributed by prescribed burning (Park *et al.*, 2007).

Over the last two decades (1990-2010), NH_3 and PM emissions from forest wildfires have significantly increased (Xing *et al.*, 2013). In the future, US fire aerosol emissions are expected to increase with the increasing forest wildfire activities linked to warming and earlier spring (Westerling *et al.*, 2006).

The feedbacks of aerosol emissions to climate are usually confined to a local scale and relatively short period. The climate effects of fire-induced aerosol emissions and their mechanisms have been broadly discussed (see Section 2). However, unlike the effects of GHG emissions, the climate impacts of aerosol emissions are much more difficult to quantify, especially at regional or continental scales. Therefore, we do not have a quantitative understanding of the climate feedbacks from fire-caused aerosol emissions in the US.

3.5 Climate feedback of fire-induced landscape albedo change

Fire-induced ecosystem vegetation change and the following vegetation succession has an impact on land surface albedo. The extent and duration of this albedo effect, however, need

careful examination. For a particular burned site, in the case of severe burning, vegetation will be cleared and surface albedo will increase. In the long term without further burning, though, post-fire succession will drive vegetation recovery to the pre-fire status (Hurteau *and* Brooks, 2011; Marlon *et al.*, 2012). Therefore for a giving site, fire-induced albedo change may be close to zero in the long term. Nevertheless, for many forest ecosystems, post-fire vegetation recovery will take hundreds of years. The albedo will be different along this recovery path. Furthermore, considering a large region like the US, every year a substantial part of the vegetation is burned. Therefore, estimating long-term albedo change caused by US ecosystem fires requires good knowledge of age distribution of post-fire recovery stands, along with the albedo of each post-fire age compared to that of the pre-fire ones.

Unfortunately, studies on land surface albedo of different post-fire successional stages are rare. One example is the research by Lyons *et al.*, (2008), which assessed the changes on surface albedo in Alaska during the first five decades of post-fire vegetation succession, with MODIS fire products. They found that fire did increase surface albedo with and without snow cover. Early post-fire successional stages have a significantly higher albedo than the control pre-fire evergreen conifer forests, in both spring and summer (Lyons *et al.*, 2008). The average shortwave surface forcing from fires over the first five post-fire decades was about -6.2 W m^{-2} relative to an evergreen conifer control (Lyons *et al.*, 2008).

However, in many other regions, albedo changes of different post-fire successional stages have rarely been quantified. The lack of such information hampers the effort to quantify the impacts of US fires on land surface albedo. Furthermore, not every burning is equal; and the recovery and post-fire succession will be impacted by fire severity. The estimate of fire-induced

surface albedo change, therefore, also needs to take in account the severity of different burnings. In the US, fires on arid and semiarid forests are usually less severe than in wet forests (Wiedinmyer *et al.*, 2011; Short, 2014). A map of fire severity, along with post-fire ages, will help in quantifying the climate impacts of US ecosystem fires.

3.6 Uncertainties in assessing the climate feedback of US ecosystem fires

Large uncertainties exist in quantifying climate feedback of United States fires. First, there are inherent uncertainties in the estimates of both burned area and fire emissions, since fires are extremely variable in time and space. For instance, burning-induced carbon emissions vary from site locations, land cover types and fire weathers (French *et al.*, 2011), and different models may have different algorithms in dealing with this high variability, resulting in inter-model differences in carbon emission estimates. This uncertainty could be reduced by the combination of isotopic and tracer techniques with regional C inverse modeling (Wiedinmyer *and* Neff, 2007). Second, the fires in United States may have introduced an "aerosol indirect effect" and an "aerosol semi-direct effect", which have not been identified to date. Third, we are not certain about the role of fire suppression in contemporary fires and the response of wildfires in response to climate change (Bowman *et al.*, 2009), while in the US fire suppression has been broadly adopted in many regions.

4. Discussions

The trend of temperature rising is highly likely to continue in the future. For instance, simulations based on the Coupled Model Intercomparison Project (phase 5, CMIP5) model ensemble using different representative concentration pathways (RCP) scenarios suggest that by the end of this century, the average US temperature is projected to increase by about 2-6 °C under

different RCP scenarios (USGCRP, 2009; IPCC, 2013; Melillo *et al.*, 2014). The increase in average temperature is also associated with more frequent extreme weathers across the US, and increased drought in the southern US (Melillo *et al.*, 2014). The frequency of lightning strikes in the lower 48 states is also predicted to increase by 12±5% in response to 1°C increase in temperature (USGCRP, 2009; IPCC, 2013; Melillo *et al.*, 2014).

The projected rise in temperature, along with increased drought and lightning strikes, is likely to cause more wildfires in the next several decades (Balshi *et al.*, 2009; Flannigan *et al.*, 2009; Marlon *et al.*, 2009; Littell *et al.*, 2010; Liu *et al.*, 2014). Modelling studies suggest that in the US, fire frequency is very likely to increase in the Southwest, Rocky Mountains, northern Great Plains, Southeast, and Pacific coast under the projected warming climate, in particular during summer and autumn (e.g., Flannigan *et al.*, 2000, 2009). The projected increasing trend in fire potential can release more GHGs and aerosols to the atmosphere and further feedback to climate.

Climate change driving increases in future fire activities highlight the enlarging demand for fire research and fire management. For future fire research, it is particularly important to couple the system dynamics of climate, fire, and vegetation (Randerson *et al.*, 2006, 2009), and the improving understanding of the feedback of ecosystem fires to climate is highly desired (Bowman *et al.*, 2009). Here we outline two research needs that we believe are critical for the improved understanding of fire feedbacks to climate-the needs for mechanistic studies, and for more inventory data of fire burnings and fire emissions. We then also discuss current and future fire management and their implications for fire burning, fire emissions, and climate feedbacks.

4.1 Mechanistic studies

Decades of research has illuminated a comprehensive picture on the mechanisms how fires and fire emissions, which are strongly affected by climate, may in turn influence climate at local, regional, and global scales. We now have an improving understanding on how fires can change radiative forcing through the emissions of greenhouse gases, aerosols, and other atmosphere chemicals, and through changes on surface albedo, surface energy and water balances (see Section 2). For example, many studies agree that fire-caused greenhouse gases emissions are one factor dominating the long-term impact of fires on climate. Yet there are many more unknowns than knowns, and we suggest that the following three processes shall be key issues in future mechanistic studies of fire feedbacks to climate.

The first one is the composition and dynamics of fire-emitted aerosols in the atmosphere and their functional mechanisms on radiation budget and the cloud formation. Products of fire emissions are a mixture of many different gases and particles that have varied optical, physical, and chemical characteristics (Urbanski *et al.*, 2008; Voulgarakis *and* Field, 2015), and we still do not know the impacts of many of them on climate quantitatively or qualitatively. In addition, many of the fire-emitted aerosol particles are transient but transportable in the atmosphere. The deposition of those aerosols in some regions, particularly those covered with snow, may bring changes on land surface albedo, water and energy balances (IPCC, 2007, 2013). This process and its contribution to local climate are also still poorly understood.

Secondly, those “first” products of fire emissions will react with each other and with existing gases and particles in the atmosphere, which result in more complex “secondary” products. Those products not only affect air quality, but also could influence local or regional

radiative budget. Yet the sign and the size of the radiative forcing by many secondary fire emission products are still a subject of further studies (e.g., Wiedinmyer *and* Neff, 2007; van der Werf *et al.*, 2010). Future studies need to clarify the mechanistic role of secondary products from fire emissions in radiative budget and atmospheric boundary processes.

Thirdly, there also remain many unanswered questions on the mechanistic impacts of fire modified land surface vegetation and water and energy balance (IPCC, 2007; Bowman *et al.*, 2009). For instance, we do not have a good understanding how canopy albedo may change with different severity of fire burning. We also know little about post-fire regeneration and vegetation succession that can modify surface roughness and the absorption and reflection of incoming solar radiation, particularly in some forested ecosystems. Fire-altered vegetation dynamic processes also have significant effects on ecosystem carbon and water cycles (Alkama *and* Cescatti, 2016), which further add to the impacts on the energy and momentum changes between land and atmosphere. We will need a coupled modelling approach with ground- and satellite-derived data to investigate the mechanisms and contribution of fire-induced vegetation dynamics to climate.

4.2 Data streams needed

The biggest challenge in quantifying the impacts of fires on climate, perhaps, may lie in the lack of high-quality and extensive data streams for fires and fire emissions. Although now there are several different data sets available for fire burned area and fire emissions, current data inventories are still far from enough to meet the research need (Wiedinmyer *et al.*, 2011; Raffuse *et al.*, 2012; Larkin *et al.*, 2014). For instance, there are considerable uncertainties among different data sets on the estimates of fire burned area and burned emissions (Section 3). Moreover, many available data sets still have significant errors or biases (Larkin *et al.*, 2014;

Short, 2014). The utilization and interpretation of those data need to be cautious.

Data of individual fire characteristics are perhaps most critical for future fire research and management need. Each fire is different in fire weather, seasonality, fire severity, burned area, fuel loading. Such information is still poorly documented, and thus created a large range of uncertainties on estimating fire burned area and emissions. For example, Larkin *et al.*, (2014) demonstrated that the great variation in fuel loading among databases is one of the largest factors responsible for the large discrepancy among different emissions inventories.

Data of fires and fire emissions are either based on ground observations, or derived from satellite products, or both. Ground observations are limited by the accessibility of burned sites. In recent years the use of satellite derived fire products is getting increasingly populous. Yet the accuracy of satellite products highly depends on the algorithms and weather (van der Werf *et al.*, 2010). More importantly, due to the limitation of their spatial resolution, many satellite fire products are unable to accurately account for small fires and prescribed burning (Giglio *et al.*, 2010; Short, 2015). GFED recently introduced an improved product that including small burned scars (van der Werf *et al.*, 2010). However, there is still a lot of work to do. The use of ground reporting fires to calibrate satellite fire products may help improve the quality of fire data streams (Hao *and* Larkin, 2014).

While there are large discrepancies among different data sets on fire CO_2 emissions, we see from Section 3 even much bigger discrepancies on other gases and aerosol emissions. One of the reasons for the much larger uncertainty in the emission of aerosols and gases other than CO_2 may be the complexity of products from biomass burning. Many fire emission inventories use

static emission factors to estimate the emissions of different species of aerosols and gases (Larkin *et al.*, 2014). However, fires can be very different in the composition of emission products due to burning severity, fire weather, fuel characteristics (Urbanski *et al.*, 2008). Future research may need to incorporate these factors in their estimation of fire emissions.

In many fire events, substantial amount of burned biomass turn into standing or fallen dead logs, which may take many years or even decades to decompose (Harden *et al.*, 2006). The gradual release of CO_2 from post-fire dead trees has not been well quantified. Also the burning of organic layers that can be a large source of gas and aerosol emissions is presently poorly represented in models and inventory databases (Raffuse *et al.*, 2012).

4.3 Ecosystem fire management

The increased spreading of fire disturbances and their consequences to Earth system and the human society have prompted policy responses. Current US federal policy regarding wildland fires is a mixture of fire suppression and the permission to use small fires to prevent to burst of large fires by reducing fuel loading (Kauffman, 2004; Stephens *and* Ruth 2005). Yet the role of either fire suppression or prescribed preventive fire burning is a subject of heated debate among scientists, property managers, and policy makers (Pollet *and* Omi, 2002; Fernandes *and* Botelho, 2003; Brotons *et al.*, 2013). The implementation of appropriate fire management policies tailored to the ecological and societal context of different ecosystem types may help halt or even reverse the increase of fire burned area under the projected warming future climate, which in turn can reduce the fire emissions to the atmosphere. Here one key issue is to recognize that fire as a fundamental ecosystem process is highly variable across geographical space, vegetation and climate types (Bowman *et al.*, 2009). Dellasala *et al.*, (2004) also suggested that interfering the

timing and intensity of wildfires might be an efficient approach to reduce the impacts of unexpected wildfires on ecosystem and human society. However, more research is needed to evaluate the impacts of alternative wildland fire policies on fire burning and fire emissions. Ecosystem fire models coupled with policy scenarios and social-economic models may be a useful tool in comparing and evaluating how different policy choices may influence future fire and fire emissions (Knorr *et al.*, 2016).

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