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Wildland fire emissions, carbon, and climate: Seeing the forest and the trees – A cross-scale assessment of wildfire and carbon dynamics in fire-prone, forested ecosystems

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ABSTRACT

Wildfires are an important component of the terrestrial carbon cycle and one of the main pathways for movement of carbon from the land surface to the atmosphere. Fires have received much attention in recent years as potential catalysts for shifting landscapes from carbon sinks to carbon sources. Unless structural or functional ecosystem shifts occur, net carbon balance in fire-adapted systems at steady state is zero when assessed over the entire post-fire successional sequence and at landscape scales. When evaluated at fine spatial scales and over short periods of time, however, wildfires may seem to release more carbon to the atmosphere than remains on site. Measurements of wildfire carbon emissions are thus highly biased by the spatial and temporal scales that bound them, and may over- or under-estimate carbon source-sink dynamics that provide critical feedbacks to the climate system. This synthesis paper provides a description of the ecological drivers of wildfires and carbon in forested ecosystems across the spatial and temporal scales at which system drivers (e.g., climate, weather), behaviors (e.g., wildfire occurrence, spread, intensity), and resulting patterns (e.g., vegetation composition and structure, carbon emissions) occur and interact. Improved understanding of these relationships is critical if we are to anticipate and respond to major changes in the global earth system expected in the coming decades and centuries.

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1. Introduction

Wildfires are an important component of the terrestrial carbon cycle and one of the main pathways for movement of carbon from the land surface to the atmosphere (Kasischke et al., 2000a,b; Baldocchi, 2008). Interest in quantifying terrestrial carbon, and concern about rising greenhouse gas concentrations and potential feedbacks of wildfire emissions to the climate system, have spurred several decades of research spanning spatial and temporal scales from stands to landscapes and seconds to centuries. Carbon accounting in fire-prone environments is highly dependent on measurement scale, including the spatial extent and time frame over which measurements occur and the ecosystem components that are measured, and may over- or under-estimate carbon source-sink dynamics (Korner, 2003; Bond et al., 2005; Alencar et al., 2006). Ecosystem carbon balance integrated over long periods of time in fire-adapted systems with constant fire return intervals is zero, meaning that carbon losses from tree mortality, wildfire combustion, and decomposition are balanced by carbon accumulation in live and dead vegetation and soils (Kurz and Apps, 1993; Harmon, 2001). However, over the short time intervals and relatively fine spatial scales of measurement that are typical of forest and fire management, wildfire emissions can tip terrestrial carbon balance from sink to source (Kashian et al., 2006; Wiedinmyer and Neff, 2007). Further, carbon emissions and carbon recovery rates vary widely depending on variables such as pre-fire vegetation composition and structure, fire severity and size, and post-fire productivity and successional trajectory (Kashian et al., 2006; Balshi et al., 2007; Wiedinmyer and Neff, 2007; Campbell et al., 2008; Meigs et al., 2009). Although wildfires happen over relatively short periods (e.g., days or months), post-fire effects may be long-reaching and profound, especially in systems that typically experience fires at 200–300 year intervals and require long periods to return to pre-fire landscape conditions (Turner, 2010).

Scale, the principle that ecological phenomena occur at multiple levels of space, time, and organization, is a fundamental and unifying concept in ecology (Levin, 1992; Schneider, 2001). Complex ecological systems have drivers, processes, and patterns that vary depending on the scale of measurement. In other words, many ecological patterns or processes that are described for a particular

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point in time and space cannot be assumed to extend to broader areas and longer time scales (Levin, 1992). Scale is a critical concept in fire-prone ecological systems, where wildfire spread that is measured over a period of seconds and linked to weather and fuel conditions at the time of fire also depends on global climate patterns that drive vegetation assemblages and produce conditions suitable for fire (Fig 1). Ecologists recognize that methods for simplifying, aggregating, and scaling ecological processes and patterns are of key importance for predicting system behavior and developing principles for management. These methods should retain information essential for understanding and attributing the mechanisms that underlie the ecological system(s) of interest, without including unnecessary detail (Schneider, 2001). Ecological literature highlights three major issues that confound cross-scale assessments and are relevant to the study of wildfires and carbon emissions: (1) there is no single natural scale at which ecological phenomena should be studied because most system processes and patterns vary with scale; (2) although many ecological processes and patterns operate across decades and broad spatial extents, most variables can only be directly measured in small areas and over short periods of time; and (3) locally measured variables generally do not scale directly to larger areas and longer time scales (Wiens, 1989; Levin, 1992; Schneider, 2001). Thus, the *scale* of an investigation of carbon emissions from wildfire has profound effects on the conclusions drawn from that investigation (Wiens, 1989). In other words, accounting for the role of wildfires in the terrestrial carbon cycle requires that we see the forest *and* the trees.

2. Wildfires and the terrestrial carbon pathway

Vegetated landscapes play an important role in storing carbon in the form of plant and animal materials (both live and dead), aboveground and in soils. Forests store about 45% of terrestrial carbon (861 ± 66 Pg C) in soils (~44% of total storage), above and belowground live biomass (~42%), deadwood (~8%) and litter (~5%) (Bonan, 2008; Pan et al., 2011). Because forests contain large reservoirs of carbon (i.e., carbon sinks) and facilitate flows of carbon from the atmosphere to the biosphere (i.e., carbon sequestration), they are an important component of the global carbon cycle and are thought to have the potential to mitigate climate change (Ingerson, 2007; Pan et al., 2011). For example, North American forests are considered important carbon sinks and currently offset about 13% of annual continental fossil fuel emissions (Pacala et al., 2007). The carbon sequestration potential of Earth's forests is about 33% of global anthropogenic emissions from fossil fuels and land use (Denman, 2007). Size and persistence of forest carbon sinks, and thus their potential to mitigate climate change, depends on anthropogenic activities such as land use and land management, and environmental factors such as vegetation composition, structure, and distribution, climate, and disturbance processes including wildfire.

Terrestrial plants remove carbon from the atmosphere though photosynthesis, which converts carbon dioxide (CO_2), water, and energy into carbon-rich plant tissues. Plants then release carbon dioxide into the atmosphere along a number of pathways, including respiration, decomposition, and smoke emissions from fires that consume plant tissues (Chapin et al., 2006). The terrestrial carbon cycle is a dynamic system with quantities and rates that vary in space (e.g., hemisphere, ecosystem) and time (e.g., decade, season). Tropical forests, for example, account for about 34% of global terrestrial total primary productivity as compared with savannahs (26%) and deserts (5%) (Beer et al., 2010). Seasonally, carbon uptake rates are highest during periods with sufficient radiation and moisture to maximize photosynthesis (Baldocchi, 2008). Global-scale climate patterns such as the El Niño-Southern Oscillation

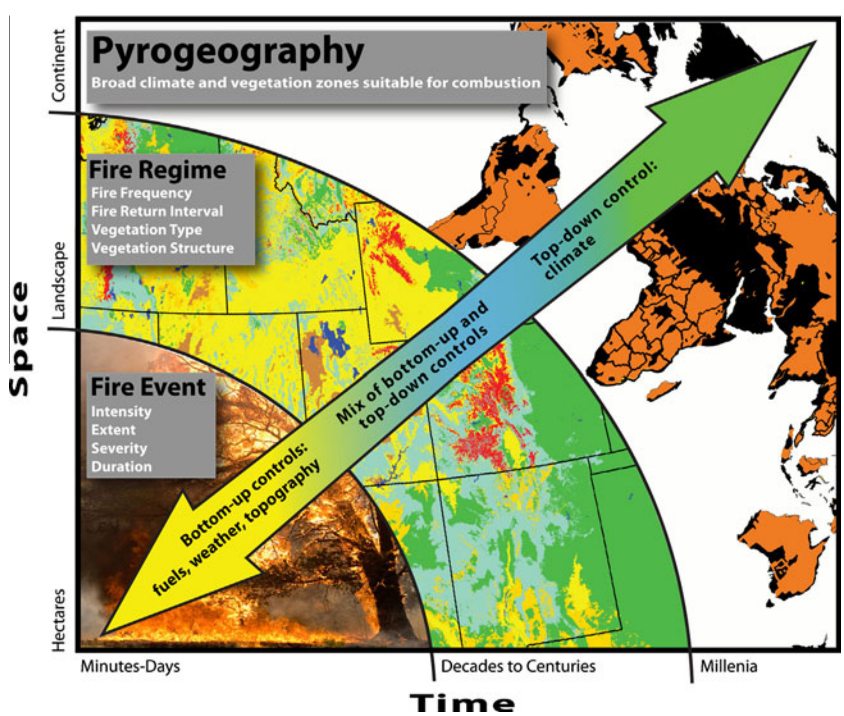

Fig. 1. Spatial and temporal scales of fire from individual, *stand* level fire events that occur over periods of days to months, to *fire regimes* that are expressed across decades or centuries at landscape scales, to continental and global-scale climate and vegetation zones that control fire patterns (*pyrogeography*) at millennial time scales. Effects of fire on carbon balance are expressed differently at each of these scales: for fire events, controls on carbon include area burned, combustion efficiency, and flaming versus smoldering combustion; for fire regimes, carbon balance is influenced by rate of post-fire vegetation recovery, vegetation composition, and successional stage; pyrogeographic influence on carbon balance is the global distribution and productivity of fire-prone formations. The fire regime panel shows historical natural fire regimes where cooler colors represent shorter fire return intervals and warmer colors are longer fire return intervals (Rollins, 2009). The pyrogeography panel shows fire-free (black) and fire-prone (orange) formations (adapted from Krawchuk et al., 2009).

(ENSO) influence the carbon cycle through local expressions of climate-landscape interactions (Denman, 2007); for example, positive ENSO anomalies can produce drought in the US Southwest, constraining CO_2 uptake by plants (Zhao and Running, 2010). Such regional droughts are linked to increases in wildfire extent and severity and forest insect outbreaks, both of which release carbon – the former through wildfire emissions and the latter through decomposition of needles and other fine fuels from attacked trees (Conard and Ivanova, 1997; Kurz et al., 2008a,b; Prentice et al., 2011).

Carbon typically accumulates in woody biomass and soils for decades to centuries until a disturbance event releases this stored carbon into the atmosphere (Goward et al., 2008). Disturbance is recognized as the primary mechanism that shifts ecosystems from carbon sinks to carbon sources (Baldocchi, 2008), and wildfire in forested ecosystems is one of the primary disturbances that regulates patterns of carbon storage and release (Kasischke et al., 2000a,b). Fire's role in carbon cycling is similar to those of respiration and decomposition, reversing the process of photosynthesis by converting stored carbohydrates to carbon emissions (CO_2, CO, and CH_4), water, and energy. The amount and rate of carbon release from a fire depends on the fire's extent and severity, as well as pre-disturbance site conditions and productivity (Dale et al., 2001; Bigler et al., 2005; Falk et al., 2007). Although long intervals between fires can allow carbon to accumulate for years to centuries, probability of fire increases with increasing time since fire (Clark, 1989). Thus fire-prone forests will eventually lose stored carbon to the atmosphere via combustion, regardless of fire and fuels management (Fig. 2).

Cross-scale interactions among key ecosystem drivers, processes, and patterns contribute to carbon emissions from wildfire (Fig. 3). We derive our concept of key system components from the field of *landscape* ecology, defined by the German geographer Carl Troll as "the study of the main complex causal relationships between the life communities and their environments…expressed regionally in a definite distribution pattern" (Troll, 1971; Wu, 2006). At landscape scales, effects of fire on stored carbon depend on pre-fire carbon stocks (the amount, composition, structure, and distribution of vegetation and accumulation and continuity of dead wood, litter, and duff), the frequency of fire occurrence, and the size, severity, and extent of burned patches (Turner et al., 2004; Kashian et al., 2006). Whether a stand within that landscape burns depends on landscape-level ignition patterns, topographic features, and climate and weather patterns that determine fuel amounts and moisture (Parisien and Moritz, 2009), as well as the risk of adjacent stands burning (Finney et al., 2011). The behavior of fire within a stand – including rate of spread, flame length, and fire intensity – varies with wind speed, fuel moisture, and surface fuel loading (Rothermel, 1972; Albini, 1976). Wildfire, climate, and vegetation, and thus fire emissions, are intimately linked across scales of time, space, and organization through environmental controls on ignitions and vegetation distributions (*pyrogeography)*, species adaptations that evolve in and are maintained by *fire regimes*, and fire behavior and effects that respond to structure, amount, and condition of fuels within a *stand* (Agee, 1993; Schoennagel et al., 2004; Whitlock et al., 2008; Krawchuk et al., 2009; Parisien and Moritz, 2009). The following sections describe the complex, integrated, and cross-scale relationships among top-down, landscape-scale and bottom-up, stand-scale controls on wildfires, emissions, and terrestrial carbon stores. Improved understanding of these relationships is critical if we are to anticipate and respond to major changes in the global earth system that are expected in the coming decades and centuries (Falkowski et al., 2000).

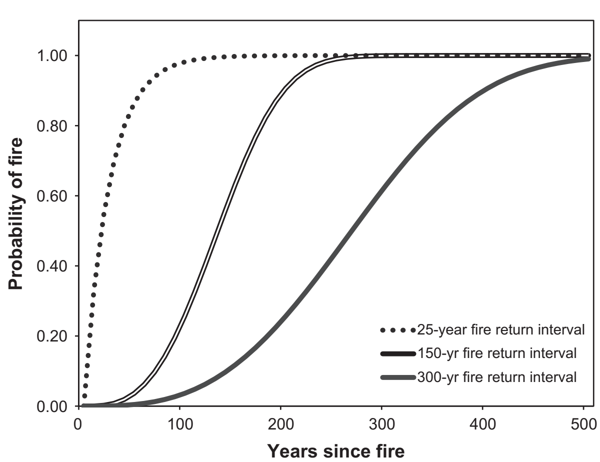

Fig. 2. Generalized Weibull fire history model showing probability of fire as a function of years since the last fire for hypothetical forest systems with 25-, 150-, and 300-year fire return intervals. The model illustrates an increasing probability of fire as time since fire increases. Depending on fire regime, carbon may accumulate for decades or centuries on a site, but it will eventually be at least partially lost when a fire occurs.

3. Fire and carbon dynamics at global and millennial scales: pyrogeography

Fire has shaped global landscapes and species, facilitated cycling of nutrients, and moved carbon across terrestrial and atmospheric domains since vascular plants dispersed across land surfaces during the Devonian era, approximately 400 million years ago (Bowman et al., 2009; Pausas and Keeley, 2009). Fire-prone vegetation types currently cover approximately 40% of the global land surface, and the persistent global distribution of these biomes, from savannahs to temperate and boreal forests, depends on fire (Bond et al., 2005). The global distribution of fire is controlled by the overlapping occurrence of combustible vegetation, environmental conditions that promote combustion, and ignitions (Krawchuk et al., 2009). In North America, wildfire emerged as a dominant process after the end of the last glacial period, about 16,500–13,000 years before present, commensurate with rapid climate changes and increased tree cover (Marlon et al., 2009). Forests today cover about 30% of the global land surface (42 million km^2), including tropical, temperate, and boreal biomes (Bonan, 2008). Many of these forest types are fire-prone and fire-adapted, meaning that fire is an integral and predictable part of the maintenance and ecological functioning.

Globally, fires, including wildfires and biomass combustion for domestic and industrial uses, produce CO_2 emissions equal to about half of those from fossil fuel combustion (2–4 Pg C $year^{-1}$ versus 7.2 Pg C $year^{-1}$) (Bowman et al., 2009; Van der Werf et al., 2010). Carbon emissions from fire vary across biomes; for example, fires in savannahs and grasslands contribute about 50% of annual emissions as compared with lesser contributions from tropical fires (about 38%) and fires in temperate and boreal forests (about 6% each) (Mouillot and Field, 2005; Mouillot et al., 2006) (Table 1). Differences in carbon emissions among biomes are due to variations in fuels, fire frequency, and fire extent (Flannigan et al., 2009).

Over the past few decades global carbon stores and fluxes have been mapped and modeled using a combination of forest inventories, satellite and other instrumental observations, and biogeochemical modeling (Emanuel et al., 1984; Hunt et al., 1996; Sellers et al., 1997; DeFries et al., 1999; Sitch et al., 2003; Houghton, 2005; Pan et al., 2011). At global scales the long-term carbon flux between the atmosphere and land surface is driven primarily by changes in forested area and shifts in forest biomass that result

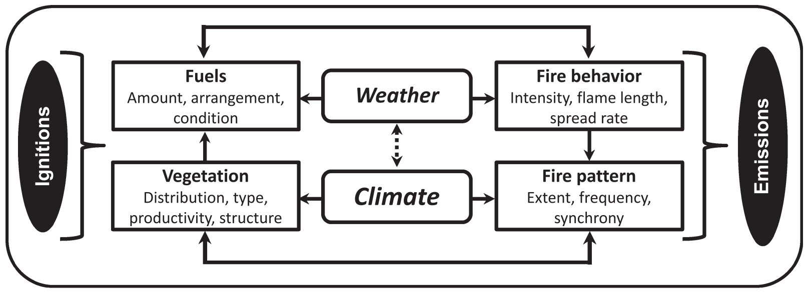

Fig. 3. Cross-scale relationships among vegetation, fuels, weather, and climate govern wildfire emissions via long-term fire patterns and short-term fire behavior processes. The process of fire is initialized by ignitions. The spread and behavior of fires depends on topographic features, climate patterns that influence vegetation, fuel characteristics that are determined by vegetation and disturbance history, and weather patterns that influence wind speed and fuel moisture. The pattern of fires on the landscape is determined by climate and vegetation through influences on extent, frequency, and synchrony of fires. The amount of carbon dioxide emitted from a fire depends on the amount of biomass consumed, influenced by the top-down, landscape-scale and bottom-up, stand-scale controls as pictured.

Table 1
Current estimated global wildland fire extent in million hectares per year and emissions in gigatons of carbon per year (Mouillot and Field, 2005; Mouillot et al., 2006).

Biome	Annual burned area (Mha/year)	Annual fire emissions (Gt C/year)	% Annual fire emissions
Temperate forest	6	0.19	5.7
Tropical forest	54	1.26	37.8
Boreal	7	0.21	6.3
Savannah and grassland	540	1.67	50.2
Total	607	3.33	100.0

from land use, land management, and regrowth (Houghton, 2005). Satellite observations can provide global-scale measurements of fire activity and area burned (Van Der Werf et al., 2006; Schultz et al., 2008; Reid et al., 2009; Vermote et al., 2009; Van der Werf et al., 2010; Wiedinmyer et al., 2011); however, global estimation of wildfire emissions is problematic because fires are highly variable in space and time and emissions estimates from fires are uncertain and hard to attribute (Wiedinmyer and Neff, 2007; Mu et al., 2011).

4. Fire effects on carbon at landscape and centennial scales: fire regimes

The role of fire in ecosystems and its interactions with dominant vegetation is termed a *fire regime* (Agee, 1993). Fire regimes are described by fire frequency (mean number of fires per time period), extent, intensity (measure of the heat energy released), severity (net ecological impact), and seasonal timing. These characteristics vary across vegetation types and depend on the amount and configuration of live and dead fuel present at a site, environmental conditions that favor combustion, and ignition sources (Agee, 1993; Krawchuk et al., 2009). Fire regimes are typically classified based on combinations of fire frequency and fire severity; these range from frequent, low-severity fires at intervals of one to 25 years to high-severity fires at intervals of 300 + years (Agee, 1993). Fire severity is specific to the structure and function of a particular ecosystem. For example, low-severity fires are typical in many ponderosa pine forests, which historically burned frequently enough to maintain low fuel loads and an open stand structure, producing a landscape in which fire-caused mortality of mature trees was rare (Agee, 1998; Jenkins et al., 2011; Moritz et al., 2011). Conversely, high-severity fires are typical in subalpine forests and tend to result in high mortality of mature trees (“stand replacement”) because long intervals between fires result in dense, multi-storied forest structures that are susceptible to crown fires (Agee, 1998). Fire regime and forest type influence carbon storage and emissions – in forests with frequent fires the relative change in carbon after fire is likely to be small and the carbon recovery rate rapid because fire severity is low. In infrequent-fire forest types high-severity fires may significantly decrease stored carbon until the forest recovers its pre-fire condition (Kashian et al., 2006; Campbell et al., 2012; Hurteau, 2013).

Much of our knowledge about fire regimes has been developed through retrospective studies that identify biophysical and climatic controls on fire frequency, extent, and area burned (Swetnam and Baisan, 1996; Falk et al., 2007; Heyerdahl et al., 2008; Littell et al., 2009). Climate is a strong driver of wildfires, and its influence on fire regimes varies by forest type and region. For example, very dry forests in the western United States are typically fuel-limited, so widespread fires occur during periods of increased productivity and fuel accumulation driven by increased growing-season precipitation. Conversely, in more mesic forest types sufficient fuel is typically available to carry fire, but suitably dry conditions for fire spread occur infrequently (Schoennagel et al., 2004). Regionally synchronous fires have generally occurred in the northern Rocky Mountains (Idaho and western Montana) during years with relatively warm spring–summers and warm-dry summers (Heyerdahl et al., 2008; Morgan et al., 2008), and in the southwestern United States following years with abundant precipitation (Swetnam and Baisan, 2003). Regional climate conditions conducive to widespread, synchronous fire are linked to global-scale coupled atmospheric-oceanic patterns such as the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO) (Swetnam and Betancourt, 1990; Trouet et al., 2006; Brown et al., 2008); these regionally synchronous fires can reduce stored carbon across large areas until vegetation communities regain pre-fire biomass.

Fire both creates and responds to landscape pattern (Turner, 2010; McKenzie et al., 2011). Fires can extend across large areas and cause long-lasting ecosystem responses, and their behaviors are conditioned by antecedent disturbance events. High-severity, stand-replacing fires can change carbon sink-to-source ratios through combustion of over- and understory vegetation and soil carbon, as well as decomposition of remaining biomass, whereas low-severity fires may retain more live and dead woody biomass and thus rapidly recoup carbon stocks initially lost during the fire event (Balshi et al., 2007; Campbell et al., 2008; Meigs et al., 2009). Areas of high-severity fire are typically interspersed across the landscape with moderate- and low-severity burned patches, forming a complex and spatially heterogeneous mosaic of vegetation types and structural stages that gradually change with time since disturbance (Turner, 2010). Heterogeneity is expressed at fine spatial scales within individual fire perimeters; for example, high-severity burned patches typically contain islands of unburned vegetation or stands that burned with low or moderate severity (Turner and Romme, 1994). Heterogeneous landscape mosaics may as a whole be more resistant to disturbance events than homogenous landscapes. For example, young forests can serve as natural fire breaks that limit crown fire spread, as was the case for fires that burned under moderate conditions during 1988 in Yellowstone National Park (Turner and Romme, 1994). Similarly, stand-replacing fires in the Rocky Mountains of Colorado create patches of small-diameter Engelmann spruce (*Picea engelmannii)* trees that are less susceptible to spruce beetle (*Dendroctonus rufipennis* Kirby) outbreaks than older stands (Kulakowski et al., 2003).

Net carbon uptake following fire depends on pre-fire abiotic and biotic conditions as well as time-dependent processes such as post-fire rates of decomposition, successional trajectories, and any long term vegetation conversion that may occur (O'Neill et al., 2003; Meigs et al., 2009). For example, repeated and spatially extensive high severity fires can remove conifer seed sources from a landscape, resulting in long-lasting conversion of coniferous forests to shrub fields, which store less carbon. In contrast, a mosaicked pattern with fires of varying severities allows for forest regeneration through seed dispersal from unburned or lightly burned patches (Donato et al., 2009). Heterogeneity in fire return intervals may increase carbon stores: model simulations (Smithwick et al., 2007) suggest that landscapes with randomly timed fires result store more carbon than those that experience fire at regular intervals. Further, heterogeneity may increase landscape resilience, defined as the capacity to maintain or recover ecosystem functions and structures during and after disturbance (Holling, 1973), by providing structural, functional, and biological redundancy (Schoennagel et al., 2009).

5. Fire effects on carbon at stand scales

When a stand burns, combustion converts a portion of the carbon on a site to emissions, producing mostly CO_2, but also carbon monoxide (CO), methane (CH_4), and particulate matter (soot and ash). The amount of carbon dioxide emitted from a fire is determined by the amount of biomass consumed by flaming and smoldering combustion (Seiler and Crutzen, 1980). Both flaming and smoldering combustion release more CO_2 and CO when fuels are very dry than under moist burning conditions, mainly due to increased combustion of duff and large woody fuels. Further, when fuels are dry high consumption of deep organic forest floor layers may occur even at low fire intensities (Brown et al., 1991; Lobert and Warnatz, 1993; Varner et al., 2007). The First Order Fire Effects Model (FOFEM) (Reinhardt et al., 1998) can be used to assess differences in stand-scale emissions from combustion of varying amounts and conditions of surface fuels. Table 2 summarizes emissions and fuel consumption estimates for an interior west ponderosa pine stand and a Pacific west Douglas-fir-western hemlock stand with typical and heavy fuel loadings, under moderate and very dry fuel moisture conditions. As described above, predicted CO_2 and CO emissions and total fuel consumption vary by forest type and fuel loading: emissions and fuel consumption are lower for the modeled ponderosa pine stand than for the Douglas-fir–western hemlock stand; within each cover type relatively more fuel is consumed and more emissions are produced for heavy versus typical fuel loads; and emissions from both flaming and smoldering combustion are inversely proportional to fuel moisture.

Combustion is governed by the amount of live and dead fuel present, fuel moisture, fire weather, and fire intensity (Finney et al., 2003; Van Der Werf et al., 2006). Surface fuel, including dead needles, leaves, fine woody debris and dead herbaceous fuels, is often completely consumed by most fires fire regardless of moisture condition, while live and dead foliage and fine branchwood on the tree may be burned in crown fires but not often in low intensity surface fires. Boles and larger branchwood of standing, live trees are typically not consumed by fires (Johnson, 1996). Occurrence of crown fires is controlled by wind, fuel moisture, surface fuel loading, and horizontal and vertical fuel continuity (Husari et al., 2006).

Conversion of biomass to atmospheric carbon continues for a long period (~100 years) after fires that cause extensive stand mortality, as standing dead trees fall and decompose (Kashian et al., 2006). Over this same time period, however, a new stand might develop on the site, resulting in recovery of carbon stocks (Fig. 4). The time required for the post-fire environment to shift from carbon source to sink varies among forest types and climates. Rothstein et al. (2004) quantified carbon in standing trees, dead wood, and soil in 11 Michigan jack pine stands of varying ages that typically burn in stand-replacement fires. Their data showed a pattern of immediate decline in ecosystem carbon after fire as dead woody material decomposed; however, after 6 years increases in carbon stored in live vegetation offset carbon losses from decomposition of dead wood, and total carbon stocks increased. In the Eastern Cascades of Oregon, Meigs et al. (2009) found that 5–6 years after fire areas that burned at low severities were a net carbon sink, while those that burned at high severities were a carbon source, although the magnitude of the source was reduced by significant belowground productivity of roots of shrubs. In other forest types, post-fire declines in carbon following stand replacement

Table 2
Estimates of CO_2 and CO emissions and fuel consumption modeled in FOFEM for interior west ponderosa pine and pacific west Douglas-fir-western hemlock stands. Results assume surface fires burning during the summer season.

	Interior west ponderosa pine (SAF 237)				Pacific west Douglas-fir - western hemlock (SAF 230)			
	Typical fuels[a]		Heavy fuels[b]		Typical fuels[a]		Heavy fuels[b]	
Emissions (g/m^2)	Moderate fuel moisture	Very dry fuel moisture	Moderate fuel moisture	Very dry fuel moisture	Moderate fuel moisture	Very dry fuel moisture	Moderate fuel moisture	Very dry fuel moisture
CO_2								
Flaming	737.6	755	1373.1	1429.1	1489.1	1903.1	3003.4	8235.5
Smoldering	1156.2	1671.5	2090.9	2986.9	14753	18605.9	29972.5	32467.6
CO								
Flaming	2.7	2.8	5	5.3	5.5	7	11	30.2
Smoldering	284.1	410.7	513.7	733.9	3624.4	4571.1	7363.6	7976.6
Percent of pre-fire fuel consumed (%)	31	40	33	43	62	78	71	85

[a] Typical fuels = "Typical" FOFEM default values for litter, duff, 1–1000-h fuels, and herb, shrub, foliage, and branch cover.
[b] Heavy fuels = "Heavy" FOFEM default values for litter, duff, and 1–1000-h fuels; "Abundant" herb, shrub, foliage, and branch cover.

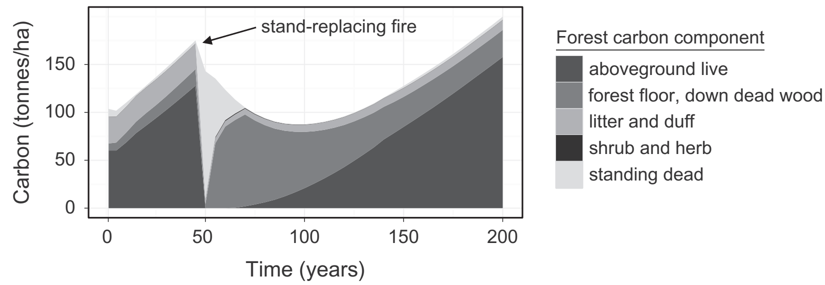

Fig. 4. Forest carbon dynamics vary temporally following fire. Here, we simulated a high-severity fire in a western Montana lodgepole pine (*Pinus contorta*) stand using the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS). Fire behavior settings included 48 km/h winds, extremely dry fuels, air temperature of 35 °Celsius, 12 m flame length, 46 m scorch height, 97% of trees crowning, and 100% of stand area burned. The fire was simulated in year 47, at which point aboveground live carbon stocks decline to zero. Although carbon emissions are significant, around 40% of pre-fire carbon stocks remain onsite following the fire as standing dead, forest floor, and down dead wood. Carbon stocks returned to pre-fire levels around 125 years following fire, When viewed over a fire return interval, the net carbon flux to the atmosphere is approximately zero.

fire might be expected to last for several decades. Reinhardt and Holsinger (2010) used the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) to examine the effects of stand-level fuels treatments on carbon-fire relationships in northern Rocky Mountain forests and found post-fire carbon recovery times of 10–50 years, depending on vegetation type and whether stands were treated before fire to reduce woody fuels. The temporal dynamics of post-fire carbon exchange are complicated by the residence times of different carbon pools, which vary from 10 to 20 years for litter in western Oregon (Law et al., 2001) to thousands of years for charcoal buried in debris flow deposits (Pierce et al., 2004).

6. Climate changes, wildfire, and carbon

Increasing interest in carbon emissions from wildfires is emerging in the context of a changing climate system. Climate changes are likely to reorganize landscapes, alter ecosystem processes and functions, and challenge our ability to predict future ecosystem behaviors and states including those that influence carbon balance. Prediction of future wildfire emissions is difficult because climate, vegetation, and disturbance interactions are complex and do not operate independently. Climate changes influence forests, and therefore forest carbon, directly – for example, drought and heat stress have been linked to increased tree mortality, shifts in species distributions, and decreased productivity (Van Mantgem et al., 2009; Allen et al., 2010; Williams et al., 2012). Climate changes also indirectly influence forests and forest carbon via wildfires, such as increases in fire frequency, fire season length, and cumulative area burned that are projected to occur in the coming decades in the western United States, in response to warmer, drier conditions (McKenzie et al., 2004; Flannigan et al., 2006). Climate changes can alter spatial distributions and amounts of fuel as a result of shifts in biotic properties of ecosystems such as dominant vegetation type, biomass, or structural stage (Lenihan et al., 2003; Loehman et al., 2011), and increase the frequency or magnitude of extreme weather events that affect fire behavior (Kurz et al., 2008b; Lubchenco and Karl, 2012). As a further feedback to the integrated climate, vegetation, and fire system changes in wildfire regimes are likely to alter landscape composition and configuration (Lenihan et al., 2003), and thus carbon emissions from wildfires. While shifts in vegetation composition and distribution due to climate alone may occur over decades or centuries, wildfires can temporarily or persistently reorganize landscapes over a period of days (Overpeck et al., 1990; Seidl et al., 2011).

Recent studies from Alaska and the intermountain western US illustrate potential interactions of climate and wildfire that influence vegetation and carbon balance. Large fires have been infrequent in the arctic tundra since the early Holocene ce. 10,000 years before present, although increasing fire is predicted to occur with warming climate (Higuera et al., 2008). The 2007 Anaktuvuk River fire in Alaska was the largest fire on record for the tundra biome (1039 km^2), doubling the cumulative area burned since 1950 (Mack et al., 2011). The fire released 2.1 Tg of carbon to the atmosphere, 60% of which originated as soil carbon, an amount approximately equal to the average annual net carbon sink for the entire arctic tundra biome over the last quarter of the 20th century (McGuire et al., 2009). Because tundra and boreal ecosystems store one third of the world's soil carbon (Post et al., 1982), a shift toward more frequent, larger fires could significantly decrease stored carbon in these biomes.

The Greater Yellowstone Ecosystem is a mainly forested area in the US intermountain west where stand-replacing fires are typically infrequent (Romme, 1982). Westerling et al. (2011) modeled the effects of climate changes on wildfire regimes in this ecosystem. Their empirical model projected a significant mid-21st century shift in fire patterns, including a decrease in the number of fire-free years and increases in the frequency of regionally synchronous fires, occurrence of extreme fire events, and total area burned. Modeled changes in fire regimes were posited to favor the establishment of low montane woodland or grassland-dominated vegetation types in place of current forests. This future landscape would likely store less carbon than is contained in today's vegetation communities.

The role of climate change in altering fire patterns remains uncertain. Grissino Mayer and Swetnam (2000) note that "long-term changes in climate.... are unlikely to produce simple linear responses in global fire regimes, e.g., warmer temperatures may not necessarily lead to increased fire frequency." Additional research suggests that increases in burned area can be expected in a warming climate, but fire activity will ultimately be limited by the availability of fuels (Torn and Fried, 1992; Brown et al., 2004; McKenzie et al., 2004; Flannigan et al., 2006; Loehman et al., 2011). Our ability to predict future fire behavior and fire effects is also challenged by an incomplete understanding of fundamental fire processes, including fuel particle ignition and fire spread, that can limit the predictive ability of fire models to narrow ranges of conditions (Finney et al., 2012). Fire behavior simulations in current fire prediction systems are based on empirical observations of fire spread, and probabilities of fire ignitions are empirical, ecosystem-specific distributions (Andrews et al., 2003; Finney et al., 2011); thus, our current models may be limited in their ability to simulate the future fire environment, should climate changes move ecosystems to new, no-analog states. To further complicate predictions, landscape-scale climate drivers interact with legacies of human land and local vegetation and fuel conditions: decades-long fire suppression and timber harvesting in some forests of the western United States have resulted in densely stocked stands and heavy downed fuels accumulation that have likely contributed to the anomalous size and intensity of recent fires (Grissino Mayer and Swetnam, 2000; Naficy et al., 2010).

7. Implications for management of forests, fires, and carbon

The purpose of this paper is to improve understanding of the ecological drivers of wildfires and forest carbon. Of central importance to the issue are the multiple spatial and temporal scales at which system drivers (e.g., climate, weather), behaviors (e.g., wildfire occurrence, spread, intensity), and resulting patterns (e.g., vegetation composition and structure, carbon emissions) occur and interact. Observing fires at only a single point in space or time presents an incomplete picture, as actual emissions measured or predicted for a single wildfire are not likely to be characteristic of emissions potential across the broader landscape or region (Higuera, 2006; Meigs et al., 2009). However, the spatiotemporal complexity of fire regimes and the stochastic nature of fire events challenge our ability to interpret landscape-scale fire dynamics (Morgan et al., 2001), particularly in real-world settings. By analyzing phenomena that occur at different spatiotemporal and organizational scales, we can better predict system behavior and develop sound and viable principles for ecosystem management (Levin, 1992). Wildland fire, including explicit simulation of live and dead fuel components, must be realistically simulated across space and time at fine scales to ensure accurate and consistent emission production estimates.

Recent studies (Hurteau and North, 2008, 2010; Hurteau et al., 2008a; North et al., 2009; Reinhardt and Holsinger, 2010) have focused on carbon responses to fire in individual forest stands as a basis for gaining insight into terrestrial-atmospheric carbon fluxes. Suggested management treatments to protect, maintain, or enhance forest carbon stocks forest carbon stores include mechanical fuels treatments, prescribed fire, and suppression of wildfires (Canadell and Raupach, 2008; Hurteau and North, 2008, 2010; Hurteau et al., 2008b; McKinley et al., 2011; Stephens et al., 2012). Results from these studies suggest that fuel treatments can reduce wildfire severity and protect forest carbon stocks from future loss from severe wildfires (Hurteau and North, 2008; Hurteau et al., 2008b; Stephens et al., 2009b), but management of carbon in fire-prone and fire-adapted forests is more complex than simply minimizing wildfire carbon emissions and maximizing stored carbon in individual stands. The stochastic and variable nature of fires, the relatively fine scale over which fuels treatments are implemented, and potentially high carbon costs to implement them suggest that fuel treatments are not an effective method for protecting carbon stocks at a stand level (Reinhardt et al., 2008; Reinhardt and Holsinger, 2010). For example, in fire-prone forests of the western US, because of the relative rarity of large wildfires and limited spatial scale of treatments, most treated areas will not be exposed to wildfire within the 10–25 year life expectancy of the treatment (Rhodes and Baker, 2008; Campbell et al., 2012; North et al., 2012). Further, some studies show that the difference in carbon emissions between low-severity and high-severity fire is small when scaled across an entire wildfire because consumption of fine surface fuels associated with low-severity fire occurs across broad spatial extents, while consumption of standing fuels associated with high-severity fires occurs in small patches within the larger wildfire perimeter (Campbell et al., 2012). Fuel treatments designed to reduce wildfire severity and wildfire-related carbon emissions have carbon costs in the form of fossil fuel emissions from harvesting activities, transportation of removed material, and milling waste (North et al., 2009). In addition, because probability of fire increases with time since fire, fires cannot be excluded indefinitely from fire-prone forests, and large surface and ladder fuel loads associated with long-unburned stands are more likely to result in high-severity wildfires and large carbon releases (Peterson et al., 2005; Stephens et al., 2009a). High carbon stocks resulting from fire exclusion and in-growth, particularly in forests adapted to frequent fire, are unlikely to be sustainable (Hurteau et al., 2011).

Fires confer ecological benefits that may (e.g., nutrient release and redistribution and stimulation of plant growth, increased productivity in soil systems from decomposition of burned material, initiation of vegetation succession and forest regeneration, increased availability of resources for surviving trees) or may not (e.g., increased plant species richness, creation of critical wildlife habitat, biodiversity and heterogeneity) be directly measurable in units of carbon (Habeck and Mutch, 1973; Boerner, 1982; Delong and Tanner, 1996; Hirsch et al., 2001; Saab et al., 2004; Turner et al., 2004; Hutto, 2008; Keane et al., 2009; Schoennagel et al., 2009). In addition, suppression of wildfires in fire-prone landscapes, while initially increasing forest carbon density (Canadell and Raupach, 2008), may increase vulnerability of systems to transformation; i.e., reduce resistance (Walker et al., 2004; Briske et al., 2006; Pausas and Keeley, 2009). Because of inherent difficulties in tracking long-term benefits of treatments, recent papers have suggested that we should question not *how* forests can be managed for carbon, but *whether* they can be managed for carbon, especially using current management practices (Mitchell et al., 2009; Campbell et al., 2012; Bowman et al., 2013).

Two complementary activities – monitoring and modeling – can improve our understanding of cross-scale ecological drivers and responses to fire. Monitoring programs can be used to quantify long-term carbon dynamics before and after fire, evaluate responses of vegetation and fire regimes to changes in climate, and identify shifts in ecosystem patterns and processes emergent under changing climates. Monitoring data can also be used to provide inputs to, calibrate, and validate models. Models, in turn, can be used to simulate emergent environmental patterns, compare effects of potential treatments, identify vulnerable landscapes or ecosystem components, and bridge gaps between landscape-scale ecological processes and variables measured in small areas and over short periods of time. There is room for improvement on both fronts; for example, the Monitoring Trends in Burn Severity (MTBS) project (Eidenshink et al., 2007) maps severity, size, and other attributes of large wildland fires in the US but does not provide primary data that characterize long-term effects of fire on biomass, carbon, tree mortality, and other ecosystem attributes. Models are used to simulate fire-carbon dynamics, but at present few modeling platforms are capable of simulating dynamic fire-vegetation-climate interactions at multiple scales and incorporating potential future conditions as ecological drivers (Loehman et al., 2011). Dynamic global vegetation models such as MC1 (Bachelet et al., 2001), LPJ (Sitch et al., 2003), and ORCHIDEE (Krinner et al., 2005) that simulate ecosystem processes at continental to global scales do not capture fine-grain fire behavior and fuel consumption, or post-fire, species-specific processes such as tree mortality and regeneration, that are important bottom-up controls on landscape carbon balance. If a model does not explicitly simulate differential fire-caused mortality at the tree level, for example, then it will be difficult to accurately map changes in vegetation structure, composition, and carbon across a larger spatial extent. Conversely, stand-scale models such as FFE-FVS, while operating in the spatiotemporal domains (i.e., finer spatial scales and shorter time periods) that are typical of management plans and treatments, do not capture the broad spatial scales and long time periods at which important drivers of wildfire and carbon operate. Characteristics of an improved modeling framework for assessing terrestrial carbon dynamics are: (1) simulation of long-term (decades to centuries) and broad-scale (landscape) processes; (2) mechanistic rather than empirical relationships among ecosystem drivers and processes, to account for novel and no-analog future environments; (3) ability to simulate synergistic interactions among disturbance processes such as climate changes, fire, and insects and diseases; and (4) spatially explicit simulation of fire behavior and fire effects, including fire intensity and severity, rates of combustion and decomposition, and vegetation mortality and regeneration. Models must also account for wildfire effects on belowground carbon pools, as forest soils retain over two-thirds of the terrestrial carbon that is attributed to forests (Dixon et al., 1994). Finally, because fire in fire-adapted ecosystems confers many important ecological benefits not measurable in carbon units, it is important to develop accounting methods that can assess ecological benefits in carbon-equivalent units so that they can be weighed against carbon losses from fire.

8. Conclusions

Understanding of fire emissions is critical for assessing global carbon balance. Forest carbon cannot be managed without accounting for the important role of wildfires in shifting carbon from the land surface to the atmosphere, and changing the rate of carbon capture. It is also critical to understand potential impacts of climate changes on wildfires and terrestrial vegetation, and account for potential feedbacks to the climate system. Currently, we know of no applied management or policy frameworks that link the spatial, temporal, and organizational domains central to understanding and appropriately and effectively managing carbon resources in fire-prone, forested ecosystems.

Turner (2010) identifies three key issues governing our ability to understand and respond to future disturbance dynamics: when, where, and how disturbances may catalyze abrupt ecological shifts (tipping points); effects of interacting disturbance processes; and feedbacks to global cycles. We suggest another key issue which is implicit in Turner's assessment: a landscape ecological perspective that can frame and direct research on carbon-fire dynamics. A landscape-scale framework requires the interfacing of the important drivers and processes that interact to produce pattern(s) of interest, as described in Fig. 3. In systems with fire return intervals of 200 or more years, the temporal period of assessment would necessarily need to match or exceed this interval. Assessment for all systems should integrate carbon fluxes across the entire landscape mosaic; i.e., measurements of carbon stocks and uptake rates at spatial scales that are larger than the boundaries of single fire events. A landscape ecological approach also requires improved understanding of long-term ecosystem responses to disturbance – delayed mortality, recovery time, regeneration trajectories, and land cover changes following wildfires. As noted by Meigs et al. (2009), the high variability of carbon responses within and among individual fire events may preclude characterization of broader trends in carbon-wildfire dynamics from plot-level assessments. Because most management tools for quantifying and predicting wildfire effects on carbon apply to relatively short temporal and fine spatial scales, comprehensive evaluation of current and future terrestrial carbon dynamics requires development of new assessment frameworks.

Carbon-fire interactions are spatially and temporally dynamic and complex and are therefore difficult to quantify and predict. We can assume that future ecosystems will be different from today's, but we cannot be specific about the patterns and processes that may emerge in the coming decades and centuries (Millar et al., 2007). The most sustainable approach to management of carbon and other ecosystem services in fire-prone and fire-dependent forests may be to restore fire to these systems (Reinhardt et al., 2008). Reintroducing fire as a landscape-scale process may reduce vulnerability to rapid and abrupt transitions and create heterogeneous landscapes that can maintain or recover ecosystem functions and structures during and after disturbance. Without such resilience, climate-fire interactions, such as potential increases in fire frequency and severity under future, warmer climates (Running, 2006), may catalyze landscape-scale, persistent shifts in terrestrial carbon balance, particularly if wildfires result in type conversion shifts from forests to shrublands and grasslands (Westerling et al., 2011). As noted by Flannigan et al. (2000), "The almost instantaneous response of the fire regime to changes in climate has the potential to overshadow importance of direct effects of global warming on species distribution, migration, substitution and extinction... fire is a catalyst for vegetation change."

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