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Chapter 5

Effects of Wildland Fire on Regional and Global Carbon Stocks in a Changing Environment

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Abstract

Every year tens of millions of hectares of forests, woodlands, and grasslands burn globally. Some are burned intentionally for land conversion, pasture renewal or hazard reduction, or wildlife habitat improvement, but most are burned by uncontrolled wildfire. Estimates of burned area available in the literature vary widely, but satellite-based remote sensing data are increasing the accuracy of monitoring active fire and estimating burned areas. Recent data suggest that global wildfire emissions vary substantially from year to year. Nonetheless, average annual carbon emissions from wildfire are 20–40% of those from fossil fuel combustion and cement production. Results of field studies and modelling efforts indicate that changing climate is likely to increase the extent and frequency of wildfires, highlighting the importance of accurately quantifying the regional and global effects of wildfire on carbon stocks and on atmospheric carbon compounds. The nature and strength of feedbacks between fire and climate will depend not only on changes in the area that is burned annually, but perhaps more importantly, on how those fires burn and how ecosystems respond and recover. Changes in burn severity can result in large differences in the amount of fuel consumed, emissions to the atmosphere, and the capacity of ecosystems to recover carbon after a fire. Recent work also indicates that even low-severity surface fire may cause significant changes in soil respiration, and these changes may either increase or decrease the net effects of fire on atmospheric carbon. Postfire recovery to a different vegetation type—which may occur in response to changing climate, unusually high burn severities, or other factors—also has the

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potential to affect the amount and rate of carbon storage on the landscape. Past and future vegetation and fire management activities also play a role in ecosystem condition and carbon storage, although the nature and magnitude of these impacts vary greatly among regions and ecosystems. Improved understanding of the extent and severity of fire, the feedbacks between fire and climate, and the effects of changing fire regimes on all aspects of the carbon cycle is needed before we can fully predict the magnitude, or perhaps even the direction, of the effect of changing fire regimes on global carbon balance and atmospheric chemistry.

5.1. Introduction

Global carbon (C) stores in vegetation and the top meter of soil are about 2500 gigatons (Gt), with 81% of this in soils and the balance in aboveground vegetation (Bolin & Sukumar, 2000). This terrestrial carbon storage is slightly over three times the amount of carbon in the atmosphere (760 Gt C). About 1146 Gt (46%) of this global terrestrial carbon storage is in tropical, temperate, and boreal forests (Bolin & Sukumar, 2000; Dixon et al., 1994); with 34% in grasslands and savannahs, and the balance in tundra (5%), wetlands (10%), and croplands (5%) (Bolin & Sukumar, 2000). In many of these systems, fire has long been a common disturbance event, whether started by lightning or intentionally or accidentally by humans. Fires in forests, savannahs, and grasslands release large amounts of carbon to the atmosphere annually, primarily as carbon dioxide (CO_2) but also in the form of other gases (such as carbon monoxide (CO) and methane (CH_4)) and aerosols, such as soot particles (Crutzen et al., 1979).

The recent report of the Intergovernmental Panel on Climate Change (IPCC, 2007) documents that climate has warmed over much of the earth in recent years. This warming, which is generally strongest in the boreal and temperate zones of the Northern Hemisphere, is expected to continue to accelerate over the next century, leading to more severe droughts and likely to more frequent and more severe fires in many parts of the world (IPCC, 2007). Such changes in fire patterns can be expected to lead to changes in atmospheric chemistry and in terrestrial carbon storage. This makes accurate estimates of effects of fire on carbon cycle and atmospheric chemistry increasingly critical.

As data sources and models improve, estimates of global and regional burned areas and of biomass emissions are changing and undoubtedly becoming more accurate. In a seminal paper, Crutzen et al. (1979) brought to the attention of the scientific community the potential importance on atmospheric chemistry of the impacts of global emissions from biomass burning. Seiler and Crutzen (1980) estimated global biomass emissions of 2.2–4.0 Gt C per year, with about 5% coming from forest fires. These estimates have been revised and refined as data and analysis techniques improve. A recent paper that integrated satellite data with ecosystem models estimated an average annual global emission from biomass burning of about 2.5 Gt C per year between 1997 and 2004, with a third to half of that from forest fires (van der Werf et al., 2006). Other recent estimates (generally for single years) have ranged from about 1.3 to 3.4 Gt C per year (Arellano et al., 2004; Hoelzemann et al., 2004; Ito & Penner, 2004; see Table 5.1 for additional examples). There is considerable research underway to validate and improve the accuracy of satellite-based estimates of burned areas (Barbosa et al., 1998; Fraser et al., 2000; Giglio et al., 2006; Roy et al., 2002, 2005).

It is reassuring that a number of recent global and regional fire emission[s] estimates are similar, given the great variability in earlier estimates (Conard and Ivanova, 1997; French et al., 2004; Ito and Penner, 2004; Soja et al., 2004a, 2004b). Considerable improvement is still needed before estimates of biomass emissions will reach the level of accuracy required for local or regional carbon accounting or estimating impacts of fire on atmospheric chemistry. Furthermore, emission components other than CO_2, such as CH_4, black carbon, and other aerosols, while emitted in smaller amounts, can have much stronger climate forcing coefficients per unit mass (IPCC, 2007). These other compounds are also not taken up through photosynthesis as vegetation regrows, although net uptake or release of methane by soils can be significant in some ecosystems (Conrad, 1996). Bousquet et al. (2006) concluded that interannual variability in atmospheric methane levels is influenced strongly by methane emissions from wetlands and less strongly by direct methane emissions from fires.

Recent estimates suggest that current average annual emissions from biomass burning are in the range 20–40% of the global annual average of about 7.3 Gt C emitted from fossil fuel combustion and cement production between 2000 and 2004 (Marland et al., 2007). Interest in the role of fire and changing fire regimes on the global carbon cycle has grown considerably in recent years as a result of evidence that unusually severe fire seasons in 1997 and 1998 in Indonesia (Page et al., 2002; Schimel and Baker, 2002), the tropics (Cochrane, 2003), and Russia (Dlugokencky et al., 2001; Kasischke et al., 2005) produced pulses of carbon into the atmosphere equivalent to close to half of annual fossil

Table 5.1. Sample estimates of fire emissions and burned areas from the literature for various years and regions. Note the wide variation in estimates from similar regions and among years and sources

Region	Year(s)	Emissions Tg C per year	Burn area 10^6 ha per year	Emissions t C/ha	Comment	Source
Indonesia	1997	810–2570	2.4–6.8	320–378	Ground sampling; fire scar analysis	Page et al. (2002)
Indonesia, New Guinea, Malaysia	1997	1090	16.7	65.6	Remote sensing; ecosystem-specific fuel consumption estimates	van der Werf et al. (2006)
Boreal zone		20–30	1.3		Very limited data available on burned area at that time	Seiler and Crutzen (1980)
Boreal zone	1998	212–422	29.0	7.3–14.5		Kasischke et al. (2005)
Boreal zone	1998	530	24.7	21.5		van der Werf et al. (2006)
Russia	Average	194	12	16.2	Based on fire return intervals and estimated consumption of available fuels	Conard and Ivanova (1997)
Russia	1998	135–190	13.3	10.2–14.3	Based on remote sensing and fuel consumption estimates	Conard et al. (2002)
Siberia	1998–2002	153–413	9.1	16.8–45.4	Annual. Average (low to high consumption)	Soja et al. (2004a, 2004b)
Eastern Russia	1998–2002	107–205	9.6	11.2–21.4	Annual. Average (low to high consumption)	Kasischke et al. (2005)
US and Canada	2002–2004	92–173	NA	NA	Low to high years	Wiedinmyer et al. (2006)
US and Canada	2002–2004	65–100	3.8–5.2	17.1	Low to high years	van der Werf et al. (2006)

US and Canada	2000	179–210	7.0–7.7		Means from two slightly different models; C emissions estimated assuming that 8% derived from CO	Hoelzemann et al. (2004)
Tropics		1800–4700			Includes deforestation, agricultural burning, savanna fire, and fuelwood	Crutzen and Andreae (1990)
Tropics	1970s	2245			Includes tropical and subtropical regions; deforestation, shifting cultivation, and savanna fires	Hao and Liu (1994)
Tropics	1997–2004	1944			Includes South America, Africa, Australia, SE and equatorial Asia, Central America	van der Werf et al. (2006)
Global		1250–2565	630–690		600 million ha of this in savannas and brushlands; not including agricultural waste and fuelwood	Seiler and Crutzen (1980)
Global	2000	1300			Satellite burned areas	Ito and Penner (2004)
Global	2000	1741	170	10.2	Satellite burned areas; excludes 0.3 million ha agricultural land	Hoelzemann et al. (2004)
Global	2000	2038	358	5.6	Satellite burned areas, regional emission factors and modelling	van der Werf et al. (2006)
Global	2000	3400			Satellite CO measurements and atmospheric modeling	Arellano et al. (2004)

fuel emissions. It is becoming increasingly clear, that these large pulses of biomass emissions are not rare or isolated instances, as the advent of improved satellite sensors has made fires easier to document and quantify.

Smoke from wildfires can move long distances, both at upper and lower levels in the atmosphere, and may affect air quality in areas thousands of miles from the source (Damoah et al., 2004; Fishman, 1991; Fromm et al., 2000; Kajii et al. 2002; Park et al., 2003; Wotawa and Trainer, 2000). This can have important implications for the effects of fires on local or regional weather and for atmospheric profiles of carbon monoxide, ozone, and other compounds. For example, Wotawa and Trainer (2000) estimated that smoke transport from Canadian fires into the United States in 1995 led to substantial increases in tropospheric CO and ozone levels across much of the eastern United States. Damoah et al. (2004) reported that smoke from 2003 fires in eastern Russia traveled completely around the Northern Hemisphere and back to Russia over a period of 17 days. While important, these effects are generally outside the scope of this chapter, which will focus on the interactions of fire with global and landscape-scale balance of carbon.

In the absence of natural or human disturbance, all forest and grassland systems would be carbon sinks, as indeed they were during Paleozoic and Mesozoic time, when much of today's fossil fuels were sequestered. As forests establish and grow, annual carbon (C) sequestration reaches a maximum rate some 30–100 or more years of age, and then the rate begins to decline. Even mature forests continue to store carbon in vegetation, litter, and soils, although the rate of sequestration may decrease greatly in older forests (Dixon & Krankina, 1993; Dixon et al., 1994; Kasischke et al., 1995; Kurz & Apps, 1999). Of course disturbance by fire, insects, or severe weather events is ubiquitous. For most forests and other ecosystems, fires have occurred for millennia, although the typical frequency and severity of fires have changed over time and vary greatly from one vegetation type to another. In a stable environment, the cycle of disturbance and regrowth can be expected to result in relatively constant levels of carbon storage in vegetation and soils, as vegetation regrowth at landscape and regional scales balances carbon losses through fire emissions, decomposition, and other processes.

General estimates of long-term trends in vegetation carbon stocks may be made from national inventories. Because such data are not available for all countries, and the intensity, frequency, and methods of data collection vary widely, inventories are not sufficient for developing global estimates. Where these data exist, they can provide an excellent overall picture of long-term trends in disturbance regimes and carbon storage, but they are less useful for determining mechanisms, evaluating changes within a landscape, determining interannual variability, or developing projections of future impacts. Furthermore, most inventory systems have also focused until quite recently on inventory of timber species, rather than on changes in soil carbon, understory plants, grassland vegetation, or other factors necessary for determining effects of fire regimes (see Birdsey & Lewis, 2003; Burrows et al., 2002; Heath et al., 2003; Kurz & Apps, 1999; Shvidenko & Nilsson, 2000, 2003, for examples of use of inventory data for analysis of long-term trends in carbon storage and impacts of disturbance on forested systems).

In this chapter we focus on the long- and short-term effects of fire on carbon fluxes revealed through remote sensing and *in situ* measurements that can provide sufficient detail to detect interannual differences in carbon storage at local to global scales. We also address the potential effects of direct fire emissions and indirect fire-related emissions on atmospheric chemistry and climate. Our primary objective is to discuss the kinds of information that are needed to develop reasonably accurate estimates of the impacts of wildland fire on carbon stocks and emissions in a changing environment. This will require a creative combination of outputs of climate models with models of vegetation dynamics that incorporate the effects of fire and with data from laboratory and field experiments that will enable researchers to accurately parameterize and evaluate their models. Some of the major areas of investigation that are needed include: improved understanding of variability in fire regimes; the drivers of and effects of variability in fire behavior; quantification of fuel consumption and emissions under a range of ecosystem and environmental conditions; and better data and models concerning processes such as soil respiration, decomposition and forest regrowth under changing environments. We will discuss a number of these issues and then provide some synthesis.

5.2. The importance of fire regime for carbon dynamics

The role of wildfire in the storage and release of carbon is largely a function of the fire regime (frequency, size, seasonality, and severity of fires, as well as the variability in these parameters) typical of a given ecosystem (see Brown et al., 2000 and Ryan, 2002 for excellent discussions of fire regime types and classification). The characteristics of individual fires may vary widely within a given ecosystem as a function of weather, fuel structure, fuel moisture, and terrain characteristics. These differences in fire regimes are a function of the combination of weather, topography, stand structure (fuels), and occurrence of ignitions that characterize specific ecosystems (Pyne et al., 1996). For example, many prairies and grasslands historically burned every few years, or even annually; dry pine forests in areas as diverse as the western United States and central Siberia burned, primarily in low-intensity surface fires, every 10–30 (or even 50) years; while cool moist conifer forests, such as coastal Douglas-fir in the Pacific Northwest of the United States burned in high-intensity stand-replacement fires only every few hundred years (Agee, 1993; Heinselman, 1978; Leenhouts, 1998; Schmidt et al., 2002).

Because vegetation that burns eventually grows back, the overall effects on carbon cycle need to be understood for individual stands over time, but ultimately integrated to a landscape level. Net effects on C storage come primarily from *changes* in fire regimes over time. In general fires that cause the most severe ecosystem effects release the most C and lead to the longest delays in recovery of ecosystem C (Fig. 5.1). These fires also tend to occur in ecosystems with the highest potential for net C storage.

In forest systems, the highest severity fires are termed *stand-replacing fires*, which typically kill all or most of the living vegetation, and burn deeply into surface litter and duff layers. These fires may release a great deal of carbon

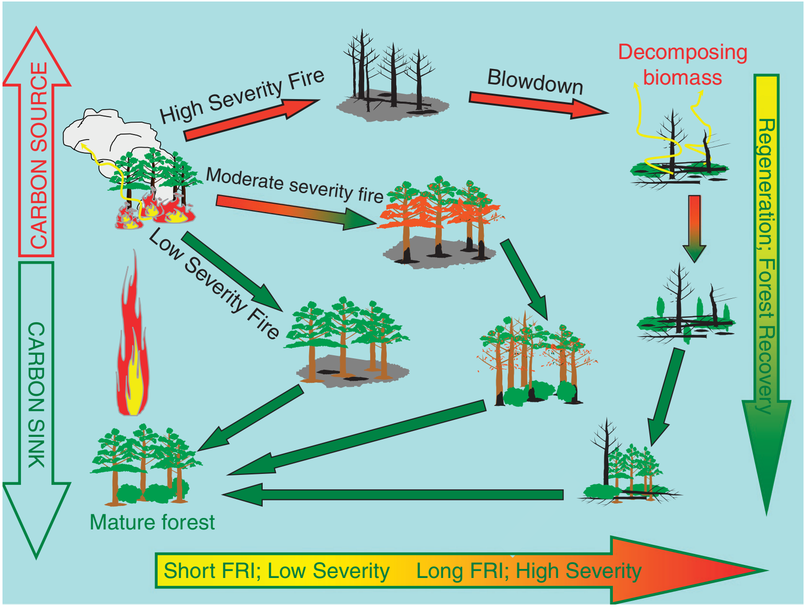

Figure 5.1. Carbon source/sink relationships in fires of varying severity as might occur in pine forest of the western United States or central Siberia (FRI, fire return interval).

and other compounds to the atmosphere, and ecosystem recovery, including return to prefire levels of carbon storage and fuel loading, is generally slow (100–300 years) (Kasischke et al., 1995; Kurz et al., 1995; Schmidt et al., 2002; Wirth et al., 2002a). Therefore, forest and shrubland systems that experience primarily stand-replacing fires tend to have relatively long intervals between fires. In some forest and shrub systems, as well as in perennial grasslands and savannas, fires may top-kill most of the aboveground biomass, but local species are adapted to recover rapidly through regrowth from live roots, basal sprouting, or other means. Such systems recover biomass (and therefore stored carbon) much more rapidly—and typically undergo a shorter interval between fires, although emissions over multiple fire cycles may be similar to those from longer interval systems.

Low-severity fires in forest systems may burn only surface fuels and low-growing vegetation, and have little impact on overstory trees beyond sometimes a brief reduction in growth rates. Such *surface fires* release relatively small amounts of carbon, but they are likely to occur more frequently, with the result that cumulative carbon release over time may be similar to that where fires are less frequent. These systems tend to have a lower potential for carbon storage than systems with less frequent, but higher-severity fires. Recent analyses and field studies have shown, however, that there can be a large range in fuel consumption and carbon emissions from even these relatively low-severity fires as a function of prefire weather conditions and details of fuel structure and consumption (Conard & Ivanova, 1997; McRae et al., 2006; Ottmar et al., 1993; Reinhardt et al., 1997; Sparks et al., 2002).

In *mixed-severity fire regimes*, relatively frequent surface fires may be interspersed with less frequent stand-replacement fires, or with patches of high-severity fire that are a function of either unusually severe weather or reduced fire frequency that leads to greater than normal fuel accumulation. This appears to be the pattern in many conifer forests in the western United States (Agee, 1998; Heinselman, 1981; Schmidt et al., 2002; Schoennagel et al., 2004), as well as the extensive Scots pine forests of northern Eurasia (Sannikov & Goldammer, 1996). In Scots pine forests in central Siberia, for example, the typical interval between low-severity surface fires is 35–50 years, with widespread stand-replacement fires occurring every 120–150 years (McRae et al., 2006).

5.3. Fire dynamics

Our understanding of the nature of fire and its effects on forests and other ecosystems comes from a combination of experimental studies (often using prescribed fire) and observations before, during, and after wildfires. These observations can occur at a range of scales using techniques such as satellite remote sensing of fires and burned areas, aircraft-based remote sensing or smoke sampling, and measurements of fluxes or changes in ecosystem properties made on the ground.

Fire effects on carbon storage and release are highly variable within and among wildfires as a function of fuel structure, fuel condition (e.g., moisture), weather at the time of burning, terrain effects, and internal fire dynamics (Pyne et al., 1996). Some of the most important differences involve the intensity (energy release) and speed of burning, which depend on the weather conditions before and during the fire, the structural properties of the vegetation, and the physical environment in which the fire occurs (Baeza et al., 2002; Brown et al., 2000; Ryan, 2002; Sandberg et al., 2002). The rate of fire spread can range over several orders of magnitude (Ryan, 2002), with the slowest spread rates in smoldering ground fires and low-intensity surface fires (e.g., less than $0.3\,\mathrm{m\,min^{-1}}$), and the fastest in crown fires (up to around $200\,\mathrm{m\,min^{-1}}$). Fires with more rapid spread rates also tend to exhibit higher energy release (intensity) and to have deeper (wider) actively burning zones (McRae et al., 2005; Ryan, 2002). The overall result, in the absence of extensive residual combustion behind the fire front, is higher fuel consumption per unit area. Residual or smoldering combustion can change this picture, particularly in areas of deep organic soils, thick humus layers, or peats—where smoldering may continue for days or even months, depending on weather conditions. Fuel consumption is more directly related to the total energy release per unit area during a fire than to other parameters, since the energy released per unit of dry biomass consumed is relatively constant. While these relationships have been evaluated in laboratory settings and from some aircraft measurements (Riggan et al., 2004; Wooster, 2002; Wooster et al., 2003), quantification of energy release from fires over large areas is just beginning to be feasible with remote sensing. Most estimates of fuel consumption in the literature are based on experimental data involving the difference between prefire and postfire fuel loading. These data show a high variability from site to site as a function of available fuels and the conditions of burning.

5.4. Fire effects on carbon dynamics

There are several components to and stages of ecosystem carbon release and uptake related to fire (Fig. 5.2). The intensity and timing of these

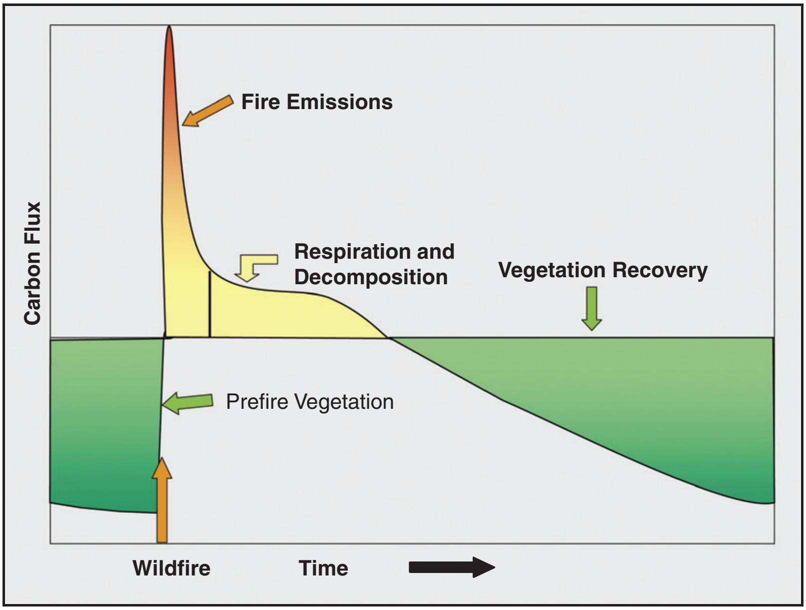

Figure 5.2. Change in net carbon emissions and storage relative to the atmosphere over time through a single fire cycle. The time scale may range from a few years to many decades depending on the ecosystem type and the severity of the fire.

fluxes is a function of the prefire fuel loading and vegetation structure, environmental conditions, and other factors that control the type of fire and the burn severity, as well as the specific ecosystem characteristics (such as adaptations to rapid recovery following fire) and the biophysical setting. The general climate and weather patterns in the months and years following the burn can strongly influence both rate and patterns of recovery.

The four major processes that drive these postfire dynamics are: (1) direct fire emissions, (2) postfire changes in soil respiration, (3) decomposition of material killed in or following the fire, and (4) postfire vegetation recovery (Fig. 5.2). Depending on the type and severity of the fire, and the ecosystem conditions before and after fire, these phases may be relatively discrete or may overlap considerably in time. Regardless, as the system recovers, at some point within months to several years the system becomes a carbon sink as carbon uptake by growing vegetation begins to dominate over carbon release from decomposition and soil respiration.

5.4.1. Direct fire emissions

The initial impact of fire on carbon flux is from the direct emissions that derive from consumption of live and dead fuels by a fire. Large fires may burn over many days or weeks. At any given point on the landscape most emissions occur during a relatively brief period of flaming combustion as the fire front passes, although there may be considerable residual combustion. Despite the common misconception that wildfires consume large amounts of tree branches and boles, most of the fuels consumed in fires are fine fuels primarily in the duff and litter layers, with additional contributions from consumption of foliage and fine twigs of living vegetation. There is typically little consumption of coarse fuels in tree canopies, even in a crown fire. This pattern is reflected in commonly used models for estimating fuel consumption (Ottmar et al., 1993; Reinhardt et al., 1997). Depending on spatial variability in fuels, terrain and other factors, and in temporal variability in winds, the severity of a fire can vary considerably across the landscape (Cochrane & Schulze, 1999; Conard & Ivanova, 1997; Key, 2006; Morgan et al., 2001), with resultant high variability in the emissions per unit area. Similar variation can occur from one fire to another. For example, Hoffa et al. (1999), working on experimental fires in woodland and grassland vegetation in Zambia, reported ranges in combustion factors (percent of fuel consumed) depending on season of burning from 1% to 47% for woodland and from 44% to 98% for grassland as fuel moisture decreased. McRae et al. (2006) reported threefold variation in fuel consumption from six experimental surface fires burned under different conditions in a relatively homogeneous stand of Scots pine in Siberia, with estimated range in emissions from 4.8 to 15.4 t C ha^{-1}. Based on allometric analysis of tree canopies, a crown fire on the same site might be expected to produce an additional 3–7.1 t C ha^{-1}; so within the Scots pine/lichen vegetation types common across central Siberia, the emissions from a given fire may range from as low as 4.8 to as high as 22.5 t C ha^{-1}.

Unfortunately, similar published data are available for few vegetation types around the world. Furthermore, we are just beginning to develop accurate global and regional databases to quantify burned areas, and information on fire severity is available only for a small percentage of the forest area burned every year. As a result, most regional to global emission estimates assume an average emission factor, either for each major vegetation or fuel type, or over the entire burned area. Several recent papers have attempted to address this problem by combining low, medium, and high surface fuel consumption estimates with estimated seasonal trends in proportions of crown fire versus surface fire (boreal zone: Kasischke et al., 2005); modelling fuel consumption based on expected seasonal trends in fire severity combined with a process-based model of ecosystem carbon stocks (global and regional: van der Werf et al., 2006); using literature-based estimates of fuel loadings and combustion factors for individual fuel types (North America: Wiedinmyer et al., 2006); or extrapolating from limited ground-based sampling to satellite-observed burned areas or hot spots (Indonesia: Page et al., 2002; some of these and other estimates are summarized in Table 5.1). There is a clear need for better data and models on which to base emission estimates from wildland fires.

5.4.2. Soil processes

It is often assumed that soil respiration will increase following fire because microbial activity would be encouraged by the increased insolation and soil moisture available after moderate to high-severity fires, along with increased availability of minerals and organic materials from dead roots (Amiro et al., 2003; Dixon & Krankina, 1993). It appears, however, that the net effect of fire on soil respiration varies widely among ecosystems. Several recent studies have reported significant decreases in soil respiration following fire in North American boreal aspen, spruce, and pine forests (Amiro et al., 2003; O'Neill et al., 2002), Siberian Scots pine forests (Baker & Bogorodskaya, 2007), and larch forests (46% decrease on year-old mild burn and 64% decrease on severe burn 5 years after fire; Sawamoto et al., 2000). Amiro et al. (2003) suggest this is a consistent pattern in many boreal forests. The magnitude of reported effects varies greatly from study to study and apparently among ecosystems. This variability likely represents real ecosystem differences as well as differences in study design, interannual variability in climate and soil moisture, and timing of sampling after fire.

In boreal forests, a number of studies have shown that depressed soil respiration may persist for several years after fire (Amiro et al., 2003). In Scots pine and larch forests of Siberia, the greatest decreases and longest periods of recovery seem to occur following higher-severity fires (Conard et al., 2004; Sawamoto et al., 2000). Several studies have suggested that decreased postfire respiration is mainly due to changes in root respiration following severe fires rather than decreases in soil microbial activity. However, a number of studies have shown substantial decreases in soil microorganism activity following even low-severity fires (Amiro et al., 2003). This is not necessarily caused by direct effects of soil heating, as the immediate postfire soil respiration in forested systems may be just about the same as the prefire respiration.

In prairie grasslands of the central United Sates, however, spring burning increased soil respiration by 38–51% relative to unburned sites (Knapp et al., 1998). Postfire increases in both soil microorganisms and soil respiration were small but significant in African savanna, although the effects of soil moisture and added organic matter were larger than those of the fire alone (Andersson et al., 2004). In ponderosa pine forests of the southwestern United States, Kaye and Hart (1998) found that restoration thinning decreased soil respiration relative to controls, while thinning along with prescribed burning increased respiration slightly, but only in the late summer. Soil respiration was the same on a burned site as on the control following surface fires in a chestnut forest in Switzerland, but increased 100–150% where surface fuel loads were artificially doubled before the fire (Wuthrich et al., 2002).

Thus, observed postfire changes in soil respiration have ranged from strong decreases in respiration on many boreal forest sites to insignificant changes or increases in respiration-related CO_2 emissions after fires in certain grassland, woodland, or dry pine ecosystems. Unfortunately, there are few studies of postfire respiration where data on fuel consumption are available. Two examples illustrate the range of potential impacts. On annually burned tallgrass prairie sites in the United States, Knapp et al. (1998) estimated that total yearly soil CO_2 emissions were equivalent to 1.3–1.4 $kg\,C\,m^{-2}$ higher than for unburned prairie. On these same sites, aboveground fuel loads (Abrams et al., 1986) suggest potential direct fire emissions of about 0.2 $kg\,C\,m^{-2}$, a mere 15% of the increase in soil respiration resulting from the burning. On Scots pine sites in Siberia, on the other hand, total C emissions from three experimental surface fires conducted in 2001 ranged from 0.44 to 0.57 $kg\,C\,m^{-2}$ (McRae et al., 2006). Soil respiration on these sites a year after the fires was an estimated 0.2–0.3 $kg\,C\,m^{-2}yr^{-1}$ lower than that on unburned control plots (Conard et al., 2004). Such a reduction in soil respiration would effectively cancel out about half of the fire emissions in just one year. Due to the potential magnitude of changes in soil respiration after fire, and the uncertainty in the direction of these changes in different systems, this is an area that clearly needs further study. In particular, assessments of impacts of fire on carbon balance require better data on how respiration changes compare with fire emissions.

Release or uptake of methane by soils and wetlands may also substantially affect the influence of fires on atmospheric emissions. Methane uptake appears highly variable as a function of ecosystem type, degree of soil moisture saturation, and other conditions (Brumme & Borken, 1999). Fiedler et al. (2005) reported methane fluxes ranging from annual emissions of 248–318 $kg\,C\,ha^{-1}$ (68–87 $mg\,C\,m^{-2}\,day^{-1}$) to CH_4

uptake of 0.1–5 kg C ha^{-1} (0.03–1.4 mg C m^{-2} day^{-1}) along a black spruce hydrosequence in Germany. They concluded that the magnitude of landscape-scale uptake of methane may often be underestimated because of exclusion of wetlands and water bodies (which emit methane) in studies of forest uptake. Gulledge and Schimel (2000) reported uptake of 0–0.5 mg C m^{-2} day^{-1} for spruce sites in Alaska. For deciduous forests in Michigan, Suwanwaree and Robertson (2005) reported average CH_4 oxidation rates of about 30 μg C m^{-2} hr^{-1} (0.7 mg C m^{-2} day^{-1}). Singh et al. (1997) reported methane uptake rates of 0.36–0.57 mg m^{-2} hr^{-1} (6.5–10.3 mg C m^{-2} day^{-1}) for dry tropical forests and savannas in India, with the lowest uptake in the wet season. In one of the few papers on effects of fire on methane uptake, Burke et al. (1997) found that carbon uptake as methane on burned upland boreal forest sites in Canada was about three orders of magnitude less than C release from soil respiration. Additional research is needed to determine the importance of soil methane fluxes to the overall impacts of fire on carbon and atmospheric chemistry.

5.4.3. Postfire carbon dynamics

Because consumption of aboveground litter, dead wood, and living biomass is seldom complete, fires leave behind varying amounts of dead organic matter, which gradually decomposes over time or may be consumed in subsequent fires. The remaining biomass is minimal following grassland fires or low-severity surface fire in forests. As forest fires increase in severity, larger trees or shrubs are killed. However, even in very intense fires, most standing woody material over 1 cm diameter is not consumed, although occasional dead trees will continue to smolder for many days. Large woody material on the ground, or that falls during the fire, may also be consumed by residual smoldering combustion. Dead trees that remain standing after a fire often decompose very little until they fall to the ground, which may take many years. Thus, the bulk of the dead material remaining after a severe fire can take a few years to centuries to decompose, as new vegetation grows to replace it. The exact time trajectory of transition from carbon source to sink following fire will be specific to the ecosystem characteristics and a function of fire severity.

Kashian et al. (2006) provide an excellent overview of the process of shifting from dominance by carbon emission to dominance by carbon sequestration and storage following stand-replacement fires in lodgepole pine forests of the western United States (Fig. 5.3). In this system standing dead trees slowly deteriorate, collapse, and then rot on the ground from 5 to 15 years after the fire. Hence, the first one or two

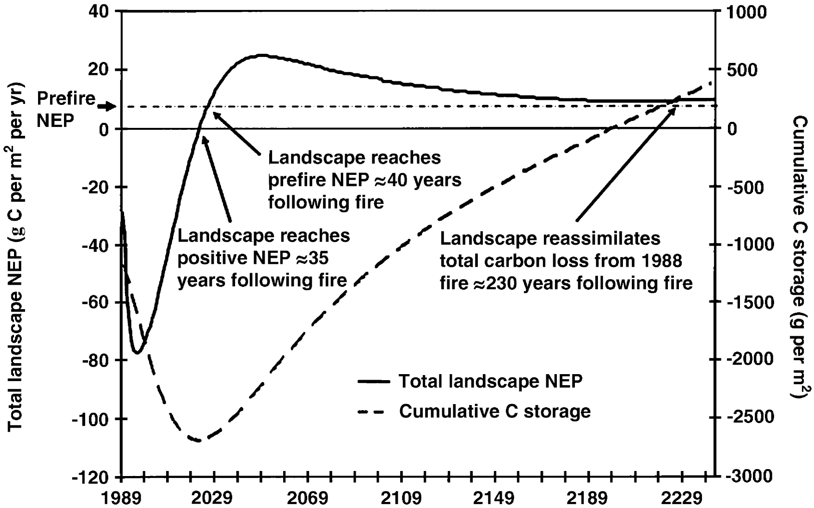

Figure 5.3. Predicted total net ecosystem production (NEP; solid line) and cumulative carbon (C) storage (dashed line) for lodgepole pine forests on the entire 525,000-hectare Yellowstone landscape following the 1988 fires. The landscape is expected to recover all C lost during and after the 1988 fires over the course of the fire interval. (*Source*: Kashian et al., 2006, Copyright, American Institute of Biological Sciences)

decades after fire are dominated by carbon release. While decomposition of dead tissue continues, annual and perennial herb and shrub species soon cover the landscape, fixing a small amount of new carbon. Tree seedlings from fire-adapted species may appear the growing season following fire or may take several growing seasons to germinate and establish. The saplings eventually outgrow the shade of the initial perennial herbs and shrubs, and at that point, the annual increment of photosynthetic tissue increases almost geometrically (Turner et al., 2004). Only after saplings are large enough to carry a leaf area index of 4 or $5\,\mathrm{m\,m^{-2}}$ or reach a height of 3 or 4 m (three to five decades) will fixation of new carbon finally predominate over emission of carbon derived from the burn. While the rate of carbon fixation (sequestration) is at a maximum at 30–50 years, the amount of carbon stored may reach its *minimum* at 20–30 years (Fig. 5.3). In lodgepole pine forests subjected to stand-replacement fires, carbon storage may not reach prefire levels for one to several centuries under stable climate (Kashian et al., 2006).

Both the timing and the magnitude of changes in ecosystem carbon fluxes may vary greatly for different ecosystems, as illustrated by Campbell et al. (2004) in a comparison of time trajectories in net ecosystem production (NEP) of western hemlock, Douglas-fir, and ponderosa pine forests in Oregon following stand-replacement disturbances. Working in Scots pine forests of central Siberia, Wirth et al. (2002b) concluded that the net postfire carbon flux was a function both of the initial amounts of coarse woody debris and the site conditions as represented by understory vegetation. Moister stands with *Vaccinium* species in the understory became net carbon sinks within 12 years after stand-replacing fire, while stands on drier sites with lichen understory took 24 years to recover to a net carbon accumulation. Fires of lower severity, or those in grassland and shrubland ecosystems, follow a similar but generally shorter chronology. Chronic climate change, especially as it reduces tree establishment and growth, or leads to changes in vegetation composition and structure, may increase the time span needed to replace emitted carbon, or may keep landscapes from ever storing as much carbon as did prefire landscapes.

5.5. Role of weather and climate on wildfire occurrence and effects

5.5.1. Interactions between ocean circulation patterns, regional climate, and fire

In mountainous areas of the western United States one of the key factors associated with severe fire seasons is the timing of snowmelt in the spring, with earlier snowmelt often being a precursor to longer summer drought periods (Westerling et al., 2006). High temperatures and low rainfall (or longer dry seasons) together produce increases in area burned and in numbers of large, intense fires (*ibid.*). Annual and multiyear weather patterns (such as those resulting from changes in El Niño/La Niña or other ocean circulation patterns) are highly correlated to the severity of fire seasons in different parts of North America, Brazil, Australia, and Eurasia.

The El Niño-Southern Oscillation (ENSO), for example, provides the southwestern United States with abundant winter rains every 3–7 years, supporting luxuriant growth of grasses and forbs the following growing season. If this pattern is followed by drought, the abundant surface fuels support development of stand-replacing fires in open woodlands, parklands, and dry pine (ponderosa) forests (Swetnam & Baisan, 1996; Swetnam & Betancourt, 1990, 1998). Recent research shows that the warm phase of the Atlantic Multidecadal Oscillation (AMO) has coincided with 40–60 year periods of increased fire frequencies throughout the western United States, and that the region appears to be entering such a period now (Kitzberger et al., 2007). These multiyear cycle effects may well amplify greenhouse gas-induced impacts of changing seasonal precipitation and temperature patterns that drive both fuel development (e.g., growth of shrubs and herbaceous species) and the severity of drought (which leads to increased fire hazard as fuel moisture decreases). In addition, the prediction of drought conditions resembling those that led to the 1930s Dust Bowl for much of the 21st century in the Southwest (Seager et al., 2007) suggests cause for serious concern regarding impending releases of carbon from these temperate zone forests and woodlands.

Similar relationships have been observed among ocean circulation patterns, drought, and fire in other regions of the world, including interactions of ENSO patterns and drought-related fire hazard in the Amazon (Nepstad et al., 2004), Arctic Oscillation patterns and fire occurrence in Siberia (Balzter et al., 2005), and the relation of ENSO to the unusually extensive fires in Indonesia in 1997–1998 (Page et al., 2002). Van der Werf et al. (2004) reported that a large anomaly in atmospheric CO, CO_2, and other compounds from August 1997 to September 1998 could be attributed largely to increased fire activity. This increase was associated with extensive droughts related to a strong El Niño, which caused unusually severe fire seasons in Southeast Asia, Central and South America, and boreal Eurasia and North America. Van der Werf et al. (2004) estimated that global fire emissions for 1997–1998 were about 1.17 (to 2.1) Gt above the 1997–2002 average of 3.53 Gt per year and accounted for as much as two-thirds of the global CO_2 anomaly for that period. The average emissions reported by van der Werf et al. (2004) for 1997–2002 are over half the 6.3 Gt C in global annual emissions from fossil fuel combustion and cement production cited earlier (Bolin & Sukumar, 2000). Although there are considerable uncertainties in the accuracy of various emission estimates, it is clear that biomass burning makes a significant contribution to global atmospheric chemistry as well as to interannual variability in global atmospheric carbon.

Drought and high temperatures interact to increase the moisture stress on vegetation. Initially this increased stress will lead to a decrease in fuel moisture that increases fire hazard and the probability of high-severity fires. As drought stress increases, trees and shrubs may lose their foliage or die. Drought stress also increases susceptibility of shrub and tree species to a number of insects (most notably bark beetles) and some pathogens. Furthermore, warmer temperatures increase the reproductive rates of some insect populations (Logan et al., 2003), permitting more intense infestations. Dried or drying foliage on trees subjected to insect attack and/or drought can increase fire hazard.

Many of the effects discussed above have occurred periodically over hundreds and even thousands of years (Kitzberger et al., 2007;

Swetnam & Baisan, 1996). However, regional climate models now project an increased frequency and intensity of fires, particularly in the boreal and temperate zones of the northern hemisphere (Bachelet et al., 2005; Brown et al., 2004; Stocks et al., 1998; Tchebakova et al., 2007; Wotton & Flannigan, 1993). Flannigan et al. (1998) point out that these effects will vary over wide regions in the boreal zone, with some areas (such as eastern Canada) expected to experience decreased fire hazard and others (such as central Canada) substantial increases in fire frequency and intensity. The recent report by IPCC (2007) projects global increases in surface temperatures particularly at high latitudes. It predicts longer growing seasons, increased heat waves, and greater high temperature extremes. Expectations for moisture pattern changes include increased heavy precipitation events, greater intensity and lengths of droughts in subtropical and lower latitude temperate regions, increased rainfall and flooding in higher latitude temperate and boreal regions, and reduced snow cover and increasing thaw of permafrost. The implications of these projections are obvious for increased boreal and temperate wildfire.

5.5.2. Potential interactions between fire and surface albedo

A more indirect effect of weather and climate involves the role of changes in surface albedo (reflectivity) from regional changes in fire regimes. Bonan et al. (1992) modelled the potential role of decreasing tree cover in boreal regions, as would occur if wildfire became more prevalent. The difference in a surface made dark by conifers masking snow, and a surface made light by snow covering the vegetation was large enough to lower temperatures in both winter and summer. Precise measurements and more intensive modelling by Randerson et al. (2006) in Alaska suggest that warming effects by release of carbon there by extensive wildfire would be entirely neutralized by cooling effects of increased albedo, at least until trees regrew.

A modelling exercise by Bala et al. (2007) projected that a temperate zone warming from carbon released by clearing all trees and forests would also be neutralized by the increased albedo of resulting grass and shrublands, although their climate model was incapable of correctly simulating the differences in evaporation that control the outcome of such an action (Thompson et al., 2004). While these studies on albedo effects are at best only somewhat indicative of potential system sensitivities, they make it clear that change in surface reflectance is an important factor to consider in determining the effects of changing fire regimes and associated changes in vegetation and land cover on climate.

5.5.3. Interactions between climate, fire regimes, and carbon

Climate change enters the fire cycle of carbon emission and carbon sequestration recovery at several points, but is particularly important in determining the fire regime and the nature of the recovery. Fire regime defines the frequency and intensity of fire across the spectrum from very frequent and moderate intensity fires that burn off accumulations of duff and kill seedlings through very infrequent but intense stand-replacing fires. Fire regime therefore determines the nature of the resulting forest ecosystem (savanna and open park-like forests to dense mesic forest) and its carbon-storage capacity. For example, Dezzeo and Chacon (2005) studied a gradient of increasing fire frequency in Venezuela that led to conversion of dense tropical forest to savanna. Along this gradient, ecosystem carbon storage decreased from 493 mg C ha^{-1} in undisturbed tall forest to 94 mg C ha^{-1} in sites that had been converted to savanna through frequent fire.

Although a mixed fire regime of 150–250 years between crown fires and 5–50 years between surface fires, such as that in Scots pine or ponderosa pine, might be expected to maintain a neutral carbon balance at the landscape scale, any change in frequency or severity of fires will alter this balance. A decline in fire return interval for crown fires can produce a severe decline in carbon carrying capacity, as time is shortened for regrowth by forests at the same time that forests may grow increasingly slowly under a climate that is chronically more stressful. An increase in surface fire severity or frequency also can generate a decline in carbon stocks, though perhaps not as great as that for crown fires (Wirth et al., 2002a).

Although we cannot predict with precision how fire regimes will be affected as climate changes, increasing frequency of drought, earlier snowmelt, decreases in permafrost, and longer fire seasons can all be expected to lead to increased fire hazard as the climate warms. A number of authors have suggested that a warming climate will cause increases in the annual area burned as well as in the severity of the fires that do occur (Fosberg et al., 1996; Stocks et al., 1998). Brown et al. (2004) used climate model projections of regional meteorology to predict a substantial increase in fire hazard by 2089 in areas of the northern Rockies, Great Basin, and the Southwest under a business as usual emissions scenario, which assumes no changes in energy policies or practices. Future changes in fire regimes can be expected to both facilitate and force changes in the structure and composition of ecosystems in a changing environment, with feedbacks that are largely unknown (Lavorel et al., 2007). Both burn severity and area burned can be expected to significantly increase, leading to higher levels of emissions from wildland fires (Overpeck et al., 1990), as well as to decreases in the amount of carbon stored in terrestrial ecosystems. In some systems in North America (such as many ponderosa pine forests) fuels have been accumulating for many years due to reduced fire frequency in the late 19th and 20th centuries (Schmidt et al., 2002). This stored carbon increases fire hazards and large, intense crown fires, a condition exacerbated by warming climate and longer fire seasons (Westerling et al., 2006).

5.6. Conclusions

Wildfire is increasingly recognized as a potentially important factor in regional and global carbon balance as well as radiative forcing in the atmosphere. Fire-related feedbacks to climate change can also be expected to occur through climate-induced impacts on vegetation structure and distribution and on fire regimes. While uncertainties remain in estimates of the level of emissions from wildfire, it is clear that global wildfire emissions are in the same order of magnitude as those from burning fossil fuels or clearing forests for agriculture. Therefore, interannual variability in burned area or changes over time in the average annual burned area or in fire severity can be expected to significantly impact overall global emissions of carbon to the atmosphere. While most of the emissions from fire are in the form of CO_2, fires also produce substantial amounts of CO, methane, carbon particulates, and other compounds that have stronger radiative forcing effects than CO_2. It is critical to consider these effects in evaluating the feedbacks between fire and changing fire regimes and climate.

The processes we must quantify to predict how wildfire will affect terrestrial *carbon stocks* are complex: fuel (carbon) consumption and fire emissions, composition of smoke, decomposition processes, soil respiration, rates of vegetation recovery, and the respective interactions of all these factors. The outcome is not as predictable as a simple increase in burning with warming that translates into more wildfire and carbon emissions. Instead, the local nature of wildfire and of ecological responses by vegetation must be understood, quantified, and modelled through research carried out at a range of scales and using a range of methods. To predict outcomes will require good field data on the range and variability of fire processes, fire effects, and fire/climate interactions in different ecosystems. The accuracy and value of modelling the climate-fire-carbon (interactions) system can be greatly improved with better understanding of ecosystem-specific responses, comprehensive data for parameterizing models, and site-specific data for evaluating their predictions.

The estimates of burned area available in the literature vary widely (Table 5.1), but accuracy is increasing as interpretations from satellite data are improved and validated. Accurate data on burned areas, their location, and the burn severity or fuel consumption for different fires are essential to improving these estimates.

Changes in burn severity can result in large differences in the amount of fuel consumed and in the capacity of the ecosystem to recover carbon rapidly after a fire. Recent work also indicates that even surface fire may cause significant changes in soil respiration—these changes can either increase or decrease the net effects of fire on atmospheric carbon. Postfire recovery to a different vegetation type—which may occur in response to changing climate, invasive species, unusually high burn severities, or other factors—also has the potential to affect the amount of carbon storage on the landscape. Past and future vegetation management and fire management activities also play a role in ecosystem condition and carbon storage, although the nature and magnitude of these impacts is a source of considerable debate.

In some years and in some regions, the carbon emissions from wildfire can exceed those from all fossil fuel sources combined. General circulation models predict that climate will get warmer and as a result, fire hazard and severity will increase over much of the globe. Studies and modelling efforts published over the past several years indicate that, especially in the boreal zone and some tropical areas, changing climate is likely to increase the extent and frequency of wildfires. As fire regimes change, we can expect that fires will be more resistant to suppression, that burned areas will increase, and that emissions per unit area will go up. As fires become more frequent, we can expect that carbon storage in terrestrial ecosystems will decrease over time.

All of this is important information to consider in evaluating the regional and global effects of wildfire on carbon stocks and on atmospheric carbon compounds. Most importantly, the intensity of feedbacks between fire and climate will depend not only on changes in the area that is burned annually, but on how those fires burn and on how the ecosystems respond and recover after the fires.

Improved understanding of the effects of changing fire regimes on all aspects of the carbon cycle is needed before we can fully predict the magnitude, or even the direction, of the effect of changing fire regimes on global carbon balance.

As a result of the uncertainties in these processes, we can define certain key research needs relative to interactions between wildfire and carbon as:

- Better historical and current data on burned area and on fire severity to help researchers analyze patterns in the past and to better project how fire regimes may change in the future.
- Improved regional projections of potential changes in climate from which to calculate changes in fire regime and in expected fuel loadings.
- Continued development of remote sensing methods to the point that they accurately measure wildfire energy release from flaming fronts and residual or smoldering combustion under the broad range of burning conditions that occur in many ecosystems.
- Increased understanding of the balance between carbon uptake and carbon emission through soil respiration over the fire cycle.
- Much greater understanding of the overall impacts of fire on radiative forcing so that the effects on the global climate of even very accurate predictions of future wildfire distributions and intensities can be assessed.
- Continued improvement of wildfire-vegetation models to validate model outputs and burned area algorithms, especially those based on analysis of remote sensing data.

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