Fire in the Earth System

S.P. Harrison, J.R. Marlon, and P.J. Bartlein

Abstract Fire is an important component of the Earth System that is tightly coupled with climate, vegetation, biogeochemical cycles, and human activities. Observations of how fire regimes change on seasonal to millennial timescales are providing an improved understanding of the hierarchy of controls on fire regimes. Climate is the principal control on fire regimes, although human activities have had an increasing influence on the distribution and incidence of fire in recent centuries. Understanding of the controls and variability of fire also underpins the development of models, both conceptual and numerical, that allow us to predict how future climate and land-use changes might influence fire regimes. Although fires in fire-adapted ecosystems can be important for biodiversity and ecosystem function, positive effects are being increasingly outweighed by losses of ecosystem services. As humans encroach further into the natural habitat of fire, social and economic costs are also escalating. The prospect of near-term rapid and large climate changes, and the escalating costs of large wildfires, necessitates a radical re-thinking and the development of approaches to fire management that promote the more harmonious co-existence of fire and people.

Keywords Wildfire · Fire regimes · Fire patterns

S.P. Harrison (✉)
Department of Biological Sciences, Macquarie University, North Ryde, NSW 2109 Australia
e-mail: sharriso@science.mq.edu

Introduction

Fire is a natural, recurring episodic event in almost all types of vegetation, although most prominent in savannas, Mediterranean woodlands, and boreal forests. Climate has a strong influence on all aspects of the fire regime, from the seasonal timing of lightning ignitions, through temperature and humidity control of fuel drying, to wind-driven fire spread. Climate also influences the nature and availability of fuel, through its influence on the productivity and type of vegetation. As the major form of vegetation disturbance, wildfires are important in regulating ecosystem dynamics, diversity and carbon cycling. Trace gas and particle emissions associated with wildfires have a major impact on atmospheric composition and chemistry and through this on climate itself. The increase in large fires seen in recent years in many parts of the world has caused major concern – not least because, while these large wildfires have probably become more frequent in response to anthropogenic climate change, the devastation caused has been exacerbated by land-use and socioeconomic changes. Indeed, the natural fire regime is being increasingly influenced by human activities. Humans set and suppress fires and use them to manage agricultural and natural ecosystems. Humans also have indirect effects on natural fire regimes – the modification and fragmentation of the natural vegetation cover through agricultural expansion and urbanization during the twentieth century, for example, has tended to reduce the incidence of wildfires. However, when wildfires do occur in proximity to settlements, the consequences from a human perspective are much greater.

J. Dodson (ed.), *Changing Climates, Earth Systems and Society*, International Year of Planet Earth,
DOI 10.1007/978-90-481-8716-4_3, © Springer Science+Business Media B.V. 2010

Wildfires are fires that are uncontrolled and unplanned, regardless of whether they are ignited by lightning or humans. Wildfires are thus differentiated from controlled burns and agricultural fires, although agricultural fires that escape may become wildfires. The complexity of fire behaviour is often simplified by characterizing wildfires in terms of regional *fire regimes* (see, e.g., Lavorel et al., 2007). The term fire regime is loosely used to describe multiple characteristics of the regional fire record, including whether the fires are a result of human or natural ignitions, the timing or seasonality of fire, the type of fire (surface or crown), the typical size of the fire (which is related to fire type), the intensity of the fire and hence its severity in terms of the amount of biomass burnt, and the characteristic frequency of fires, or return time (see, e.g., Gill, 1977; Bond and Keeley, 2005). Changes in the external controls on fire may provoke simultaneous changes in several of these characteristics, but they can also change independently. Furthermore, given that climate varies continuously on decadal to millennial timescales, characterizing regional regimes solely in terms of frequency or return time is not helpful. Thus, while it is useful to continue to use the term fire regime to describe various aspects of fire behaviour, it is important to realize the dynamic and ever-changing nature of fire regimes.

From an Earth System perspective, fire is an important global process that is tightly coupled with climate, vegetation, biogeochemical cycles, and human activities. Improved understanding of the role of fire requires an approach that recognizes this interconnectedness, and as Bowman et al. (2009) have recently argued, there is an urgent need to develop a coordinated and holistic approach to fire science in order to manage fire better. In this chapter, we draw on empirical observations and modeling work to characterize pyrogeography, emphasizing the links between climate and fire (e.g., via examination of the variation of fire in time and space), fire and climate (e.g., via effects on radiative forcing), fire and vegetation (e.g., via feedbacks to the climate system that in turn drive further vegetation changes), and fire and human activities (e.g., via explicit as well as hidden economic costs). This holistic approach provides a long-term and broad-scale context for current fire regime changes and draws attention to the role of fire as a catalyst as well as a consequence of global environmental change.

Observations of Wildfire Regimes

There are many different sources of information on wildfire. However, these sources differ widely in their purpose, type, scale, quality, temporal and spatial resolution, and processing methods, making comparisons and integration of information about fire across a range of temporal and spatial scales challenging. Nevertheless, there are global-scale data sets that document how the spatial patterns of fire change on a variety of different timescales ranging from seasonal, through interannual, decadal or centennial, and to the multi-millennial or longer-term variability shown in geologic records (Fig. 1).

Contemporary Fire Patterns

Satellite remote sensing systems are now the primary means for studying the contemporary and recent temporal (Fig. 1a) and spatial (Fig. 2) variability of fires because only remote sensing can provide detailed and consistent information from regional (e.g., Sukhinin et al., 2004; JRC-EU, 2005; van der Werf et al., 2008a) to global scales (Carmona-Moreno et al., 2005; Giglio et al., 2006; Mota et al., 2006; Randerson et al., 2007; Frolking et al., 2009). Such data are especially critical for documenting fire in remote areas, such as in the boreal forest, where ground-based data are exiguous. Remote sensing systems identify the areas burnt by fires and also can detect active fires (i.e., the energy radiated by fire: Ellicott et al., 2009). Emissions of trace gases and particulates are not measured directly but are commonly estimated as the product of burnt area, fuel load, and combustion completeness for a particular time interval and spatial domain (van der Werf et al., 2006). Burnt areas from past fires are determined by analyzing the unique signatures left by charred vegetation and patterns of regrowth after fires (Giglio et al., 2006).

Most of the fire-related global products available document variations in burnt area (e.g., Carmona-Moreno et al., 2005; van der Werf et al., 2006; Riaño et al., 2007; Roy et al., 2008; Tansey et al., 2008) or in the presence and timing of active fires (Giglio et al., 2006). There are still substantial differences between the available products, in part a result of the different sensors and approaches used and in part because

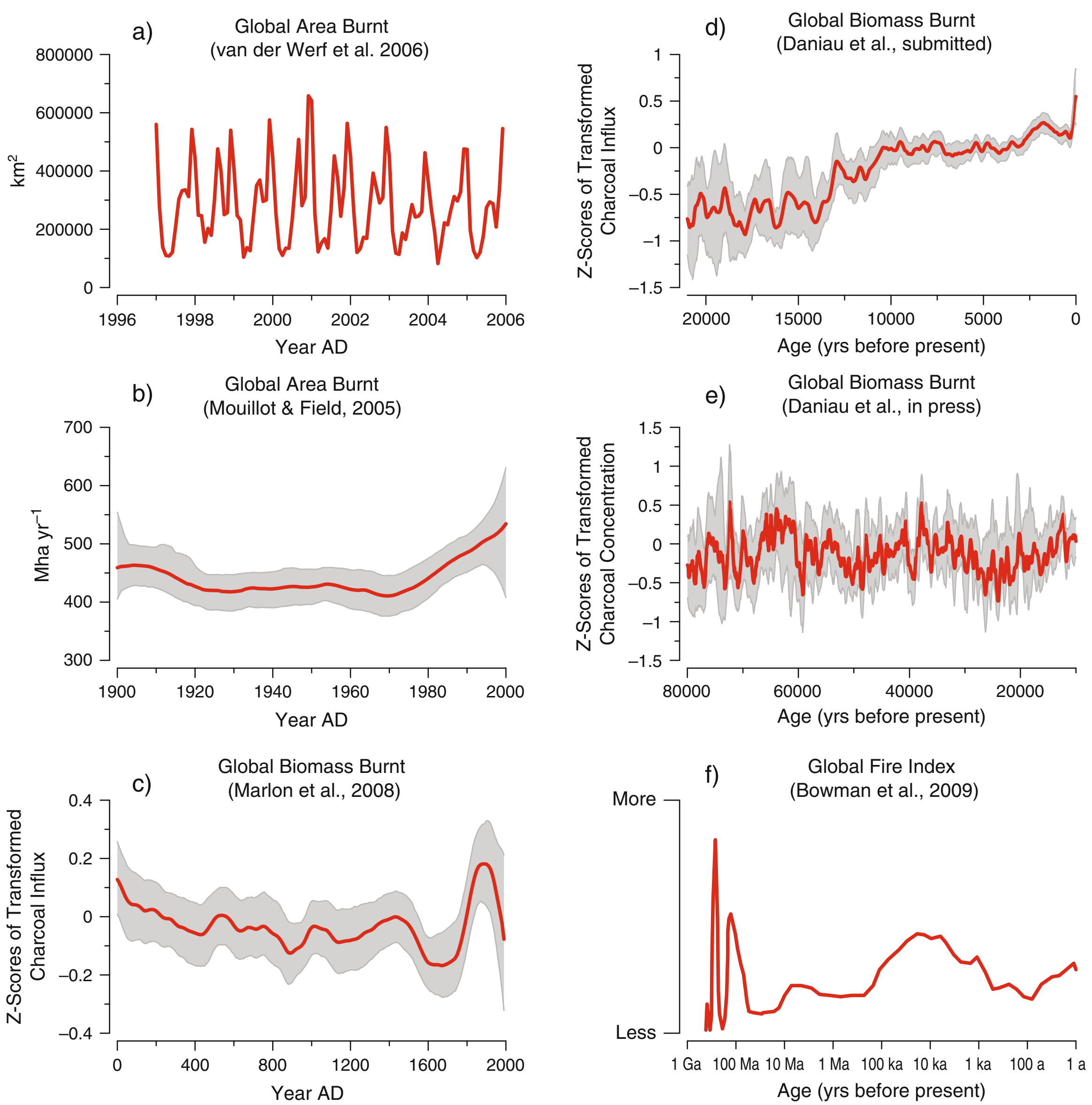

Fig. 1 Variability in global fire on different timescales. **a** Global area burnt from 1997 to 2006 derived from satellite-based remote sensing (GFED v2.1, van der Werf et al., 2006). **b** Global area burnt over the twentieth century, estimated by combining data from tree-ring, historical and remotely sensed sources (Mouillot and Field, 2005). **c** Estimates of global biomass burnt over the past two millennia, based on compositing ca. 400 sedimentary charcoal records worldwide (Marlon et al., 2008). **d** Estimates of global biomass burnt since the Last Glacial Maximum, ca. 21,000 years ago, based on compositing ca. 700 sedimentary charcoal records worldwide (Daniau et al., submitted). **e** Estimates of global biomass burnt during the last glacial (ca. 80–11,000 years ago), based on compositing 30 sedimentary charcoal records worldwide (Daniau et al., in press). **f** A qualitative index of global fire over the past 1 billion years based on discontinuous sedimentary charcoal records (Berner, 1999)

each product covers a different interval of time. van der Werf et al. (2006) have reconstructed global variations in fire from 1997 to 2004 (Fig. 1a) by combining fire data from several remote-sensing instruments including the Moderate Resolution Imaging Spectroradiometer (MODIS), Along Track Scanning Radiometer (ATSR), the Visible Infrared Scanner (VIRS) and the Advanced Very High Resolution Radiometer (AVHRR). Newer satellite products provide additional information about the radiative energy

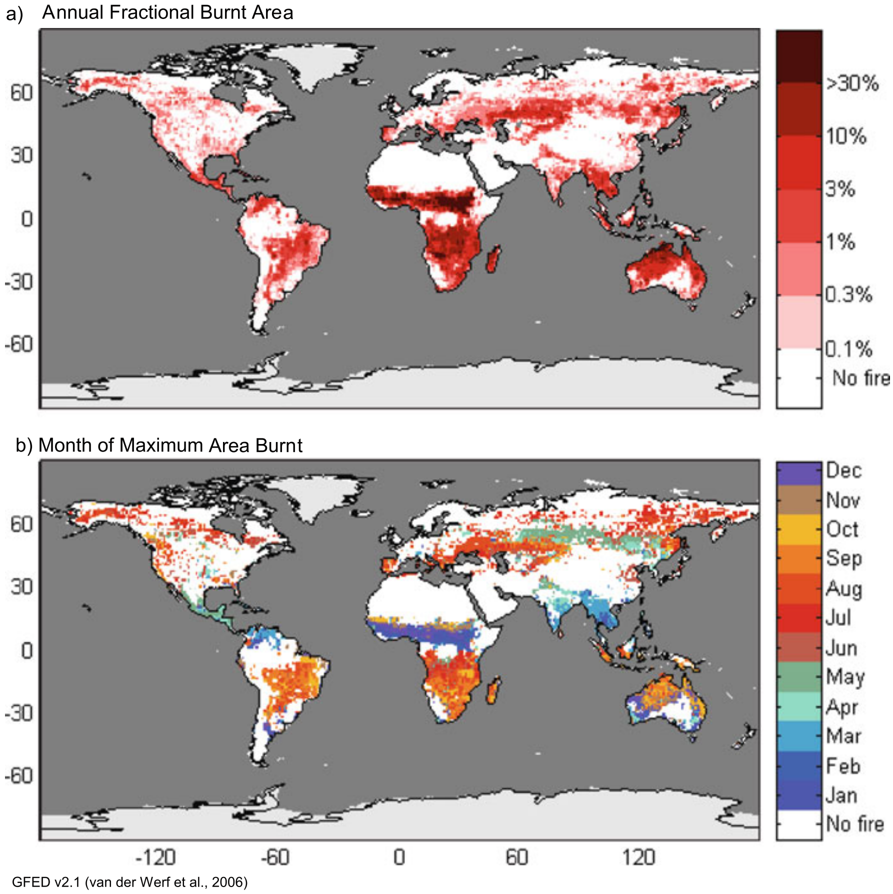

Fig. 2 Spatial patterns in fire regimes under current climate conditions. **a** Annual fractional burnt area and **b** observed month of maximum burnt area for regions where the fractional burnt area is greater than >0.1%, both averaged over 1997–2006, from GFED v2.1 (van der Werf et al., 2006)

released by fires (Ickoku et al., 2008) and thus provide information about fire type (Smith and Wooster, 2005).

According to the GFED 2.1 data set (van der Werf et al., 2006), 3–4 Mm^2 of land burns every year, and fires are relatively frequent on about a third of the land surface (Chuvieco et al., 2008). The largest fractional areas burnt occur in tropical and subtropical regions of South America, Africa, Southeast Asia, Indonesia, and Australia (Fig. 2a). Africa accounts for 40% of the global area burnt. Most African fires are concentrated in the Sahelian and Sudanian regions of sub-Saharan Africa and in southern Africa (Silva et al., 2003). There is much heterogeneity within these broad regions, with semi-arid regions burning less due to fuel limitations, and wetter areas burning more as a result of greater fuel availability (van der Werf et al., 2008b; Archibald et al., 2009). Fire is also a common feature in the tropical and subtropical regions of South America and Australasia. There has been a long history of fire in seasonally dry tropical forests in these regions, but the present level of burning in Amazonia and Indonesia was attained only in the last few decades and reflects human use of fire to clear forests for crops and pastures (so-called deforestation fire). Fires in temperate and boreal forests are less frequent than those in the tropics but, when they occur, consume large quantities of biomass (Kasischke and Bruhwiler, 2002; Campbell et al., 2007).

The most striking pattern in the timing of the fire season is the transition between a tropical region with winter (dry) season dominance and an extratropical region with summer (warm) season dominance (Fig. 2b). This pattern is seen in both hemispheres.

Superimposed on this pattern is the tendency for drier, fuel-limited regions in the subtropics to experience peak burning in the autumn, as fuel dries after the peak growing season. Thus, maximum burning tends to occur from December to February in the Sahel, India, and Central America, during October and November on the Saharan margin, and during July through September in southern Europe and North America. In the southern hemisphere, peak burning in the tropics and subtropics of southern Africa, Australia and South America occurs during July through September, while December through February marks the peak fire season in the southern mid-latitude regions.

The global record of fire over the last decade (Fig. 1a) is dominated by the northern hemisphere seasonal cycle. Nevertheless, the GFED record shows interannual differences of the order of 10% (ca. 0.3 Mm^2) around the long-term mean value of area burnt (van der Werf et al., 2006). There is no discernible trend in the total area burnt over this relatively short interval (1997–2006), but an AVHRR-based reconstruction of relative changes in burnt area covering the period 1982–2000 (Riaño et al., 2007) shows a trend toward increasing fire over this longer interval. This latter data set also shows substantial interannual variability, including a marked transient reduction in global burnt area after the El Chichon (1982) and Pinatubo (1991) volcanic eruptions.

Historical Records of Fire

Although many countries now collect statistics on fires, these records rarely extend back more than a few decades (http://www.fire.uni-freiburg.de/) although there are some records, e.g., national parks or managed forests that extend back to the first decades of the twentieth century (see, e.g., Fulé et al., 2003). Information on earlier fires is largely anecdotal, inferred from historical documents, photographs, ethnographic records or other archives (see, e.g., Habeck, 1994). Much of the available information is biased toward fires that resulted in destruction of infrastructure, even if these fires started naturally. More consistent longer-term fire records can be obtained from fire scars in tree-ring records (Swetnam, 1993; Kipfmueller and Baker, 2000; Kitzberger et al., 2001) and forest stand-age data in areas with high-severity, stand-replacing fires (Kipfmueller and Baker, 2000; Hallett et al., 2003). Both sources can provide records covering several centuries or even, in rare instances, millennia but only provide information at local to subcontinental scales.

Mouillot and Field (2005) combined data from historical, dendrochronological, and satellite-derived fire records with information about vegetation, population, and land-use changes to reconstruct trends in annual area burnt during the twentieth century (Fig. 1b). Interpolation and smoothing techniques were used to fill gaps and remove artifacts introduced by the different data sources. As a result the estimates are highly uncertain but, despite these problems, a smoothed summary trend of the data shows features consistent with independent evidence of variations in twentieth century burning, including a decline in fire activity at the beginning of the century and an increase in area burnt during recent decades. The early twentieth century decline in burning is consistent with a long-term global decrease in biomass burnt that has been independently inferred from charcoal data (Fig. 1c) and dendrochronological studies (Veblen et al., 1999; Grissino-Mayer et al., 2004; Drobyshev et al., 2008), and the late twentieth century increase in area burnt is consistent with local- to regional-scale observations (Cochrane, 2003; Girardin, 2007; Fisher et al., 2009) and with satellite and model-based reconstructions (Pechony and Shindell, 2009).

Paleofires

Burning vegetation produces charcoal, black carbon, and carbon spherules that accumulate naturally in lake sediments, peat, soils, and marine sediments (Tolonen, 1986; Ohlson and Tryterud, 2000; Conedera et al., 2009; Power et al., 2010). The rate of sediment accumulation, which depends on the type of site, its geomorphic setting, and the control on erosion rates exerted by topographic, land cover, and climatic factors, determines the temporal resolution of these records. In some cases, annually laminated sediments have been used to explore year-to-year or multi-year variation in biomass burning (Clark, 1990; Atahan et al., 2004; Power et al., 2006) but in general paleo-records provide continuous reconstructions of changing fire regimes on decadal or centennial timescales (e.g., Walsh et al., 2008). Many hundreds of individual charcoal records have been generated, from all regions of the world. Although these records cannot provide quantitative estimates of biomass burnt, they can be interpreted in terms of relative changes in biomass burning at subcontinental to global scales (see e.g., Haberle and Ledru, 2001; Carcaillet et al., 2002; Marlon et al., 2008; Power et al., 2008; Daniau et al., in press; Daniau et al., submitted).

The global sedimentary charcoal records for the past two millennia (Fig. 1c) show a long-term decline in biomass burning between 1 AD and ~1750 AD, with centennial-scale variability associated with known climate fluctuations including the Medieval Warm Period and the Little Ice Age (Marlon et al., 2008). The largest changes in global biomass burning occur during the past ~250 years, when warming after the Little Ice Age coincided with major changes in population and land use. The records show an initial increase in biomass burning, but after ca. 1850 AD there is a pronounced decrease. Marlon et al. (2008) have argued that because this downturn pre-dates the introduction of active fire-fighting, it is most plausibly explained as an inadvertent consequence of human activities, resulting from landscape fragmentation and reduction of fuel in intensively managed agricultural landscapes.

Charcoal records also provide information for long-term trends during the last climatic cycle (Power et al., 2008; Daniau et al., in press; Daniau et al., submitted). Biomass burning was low during the coldest intervals during the past climatic cycle, Marine Isotope Stage 4 (73.5–59.4 ka) and Marine Isotope Stage 2 (27.8–14.7 ka), increased during the warmer, interstadial interval of Marine Isotope Stage 3 (59.4–27.8 ka), and has generally increased toward modern levels since the Last Glacial Maximum ca. 21,000 years ago (Fig. 1d). There are sufficient sites covering the last deglaciation to show that fire regimes in the northern and southern hemispheres during the deglaciation (Daniau et al., in press), a relationship first identified in temperature records from the polar ice caps (EPICA Community Members, 2006) and consistent with the association of these temperatures with changes in the strength of the Meridional Overturning Circulation. Both the past 21,000 years and earlier periods of the last glacial (Fig. 1e) are characterized by millennial-scale variability in fire regimes, tracking the Dansgaard-Oeschger (D-O) climate cycles seen in the Greenland ice core record and the Heinrich Stadials recorded in the North Atlantic (Marlon et al. 2009; Daniau et al., in press). There is an increase in fire, seen both at a global scale and at a continental scale in North America, during the rapid D-O warming events (Fig. 1e). Fire initially decreases during D-O or Heinrich cooling intervals, but then recovers to pre-cooling levels. Analyses of multiple climate cycles suggest that the response of fire to the recorded climate changes is extremely fast (Fig. 3).

There are fewer highly resolved records of biomass burning over time scales longer than the last climatic cycle. The longest continuous record of biomass burning is a million-year-long black carbon record from marine sediments in the eastern equatorial Atlantic (Bird and Cali, 1998; Bird and Cali, 2002). This record represents fires in sub-Saharan West Africa and shows large episodic increases in fire activity. Periods of high burning occur during some interglacials; no fire is recorded during glacial periods.

Older geological records of fire (Fig. 1f, Bowman et al., 2009) show that burning occurred on Earth at least as long ago as the Silurian (ca. 420 million years ago) and Carboniferous (ca. 400 million years ago) (Glasspool et al., 2004). The Permian (ca. 250–300 million years ago) was also characterized by high levels of fire. On such long time scales, variations in atmospheric oxygen are thought to be the primary control on whether and how much fire was possible (Scott, 2000; Scott and Glasspool, 2006). Experimental studies suggest fire cannot be sustained when the oxygen content of the atmosphere is below about 15% (Jones and Chaloner, 1991; Belcher and McElwain, 2008). At oxygen levels above ca. 35%, wildfires would consume most terrestrial vegetation (Scott, 2000; Lenton, 2001). Modeling experiments suggest that the abundant charcoal found in Carboniferous and Permian sediments may reflect widespread wildfires that occurred once atmospheric oxygen increased above ~21% (Berner, 1999). The Paleocene-Eocene thermal maximum (ca. 65 Ma) was also characterized by major increases in biomass burning (Collinson et al., 2007; Marynowski and Simoneit, 2009). Peaks in charcoal in marine sediments ca. 7–8 million years ago (Fig. 1f) are contemporaneous with the expansion of open grasslands and savanna vegetation globally (Keeley and Rundel, 2005).

There is a high degree of variability in fire-regime patterns at different temporal scales, and this is more

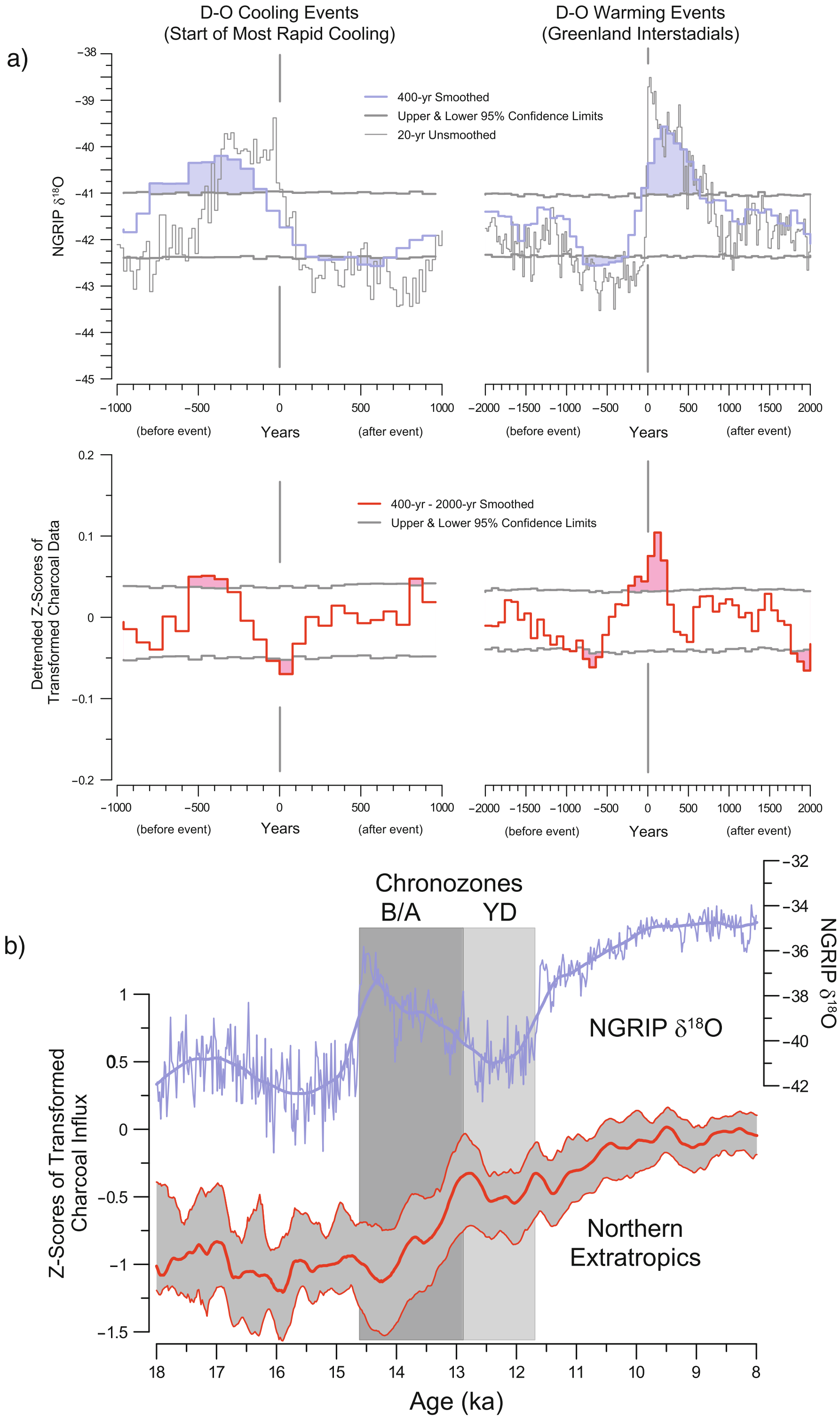

Fig. 3 The response of fire regimes to rapid climate changes. **a** Superposed epoch analysis of ice-core and biomass-burning records over the interval 80–10 ka, showing the response of fire to rapid cooling and warming intervals during the Dansgaard-Oeschger cycles (Daniau et al., in press). **b** Comparison of the temporal evolution of composite charcoal records from the northern extratropics through the Younger Dryas chronozone (Daniau et al., submitted), which, as shown by the ice core record, was characterized by rapid cooling and subsequent rapid warming on the order of 10°C in Greenland in about a decade

than a reflection of differences in data sources and methodological approaches. Satellite data show clear seasonal cycles in fire, but at longer timescales changes in fire are more episodic than periodic. Although regional fire regimes are often characterized in terms of return times, such regularity can only be maintained as long as the major drivers of fire activity, including climate conditions, vegetation cover and ignition sources remain unchanged. Both historical and paleo-records suggest that stability is the exception rather than the norm.

Controls of Fire

Globally (Fig. 2a), fire is controlled by climate (Carmona-Moreno et al., 2005), which on short time periods produces the familiar cycle of seasonal burning (Fig. 1a). Seasonal variations in climate are driven by gradual increases and decreases in insolation that result from the movement of the Earth around the Sun. These insolation-driven climate changes are generally characterized by large temperature changes during the year at mid- and high latitudes, and by changes in precipitation at lower latitudes. Temperature and precipitation interact to determine vegetation growth, composition, and structure, which in turn influence the patterns of fuel loading and moisture that directly determine fire spread, severity, extent, and related factors (Stephenson, 1998; Dwyer et al., 2000), and hence the seasonal variations in the incidence of fire (Fig. 2b). The importance of fuel load versus fuel moisture varies across climate gradients. In arid environments, lack of precipitation constrains vegetation growth making fuel availability the primary limiting factor on the occurrence and spread of fire. In moist environments, fuels are abundant but their flammability is limited by the length and intensity of the dry season (Westerling et al., 2003; van der Werf et al., 2008b). In the wettest climates, fuels never dry sufficiently to burn.

Fire tends to occupy intermediate environments in terms of climate, vegetation, and human population. This generalization is supported by the distribution of area burnt along climate and vegetation-productivity gradients, such as available moisture versus net primary productivity (Fig. 4a). The largest annual area burnt tends to be in regions with net primary productivity between about 400 and 1,000 gC/m^2 and with intermediate levels of moisture availability (between 0.3 and 0.8 on an index of actual to potential evaporation, AE/PE). Fire is largely absent from extreme environments, such as low tundra, deserts, and semi-arid regions where sparse vegetation results in discontinuous fuel loads that prevent the spread of fire. Fire is also rare in temperate oceanic margins and in tropical rainforests, where the fuel is too wet to burn. It is remarkable that the extremely heterogeneous pattern of fire in geographical space (Fig. 2a) reduces to a single broad maximum of fractional area burnt when plotted in climate and vegetation space (Fig. 4a).

Comparing the distribution of fire against those of biomes along NPP and AE/PE gradients shows that seasonally dry tropical forests, savanna and dry woodlands have the largest annual area burnt (Fig. 4b), while grassland and dry shrublands, and temperate and boreal forests have intermediate annual area burnt. Deserts and tundra have the lowest annual area burnt. These patterns are consistent with the preferred "habitat" of fire in woodlands, shrublands, and seasonally dry forests with intermediate levels of biomass accumulation and seasonal moisture stress.

Fire similarly is prevalent at intermediate levels of lightning and population densities (Fig. 4c, d). Fire is rare where lightning is infrequent, not necessarily because ignition is a limiting factor but because climate limits both lightning and fire for different reasons: lightning is less frequent in high than in low latitudes because of lower convective activity in high latitudes, whereas fire is less frequent at high than at low latitudes because of limited fuel availability. Fire is also rare where lightning is most common – in tropical rainforests – because the fuel is rarely dry enough to sustain combustion. Lightning is only rarely considered to be an important limiting factor, such as in the Chilean mattoral and in North American coastal rainforests during the early Holocene (Fuentes et al., 1994; Brown and Hebda, 2002). Comparison of the distributions of lightning, vegetation, and fire (Fig. 4a, c) shows that there is abundant lightning in most regions of low burnt area, except in the tundra.

Population densities and fire are not related in any simple way (Fig. 4d). Regions with the highest burnt area have intermediate levels of population. Overall, the distribution of population resembles that of vegetation more fire, with low population densities in tundra, boreal forest, and tropical forest biomes. In

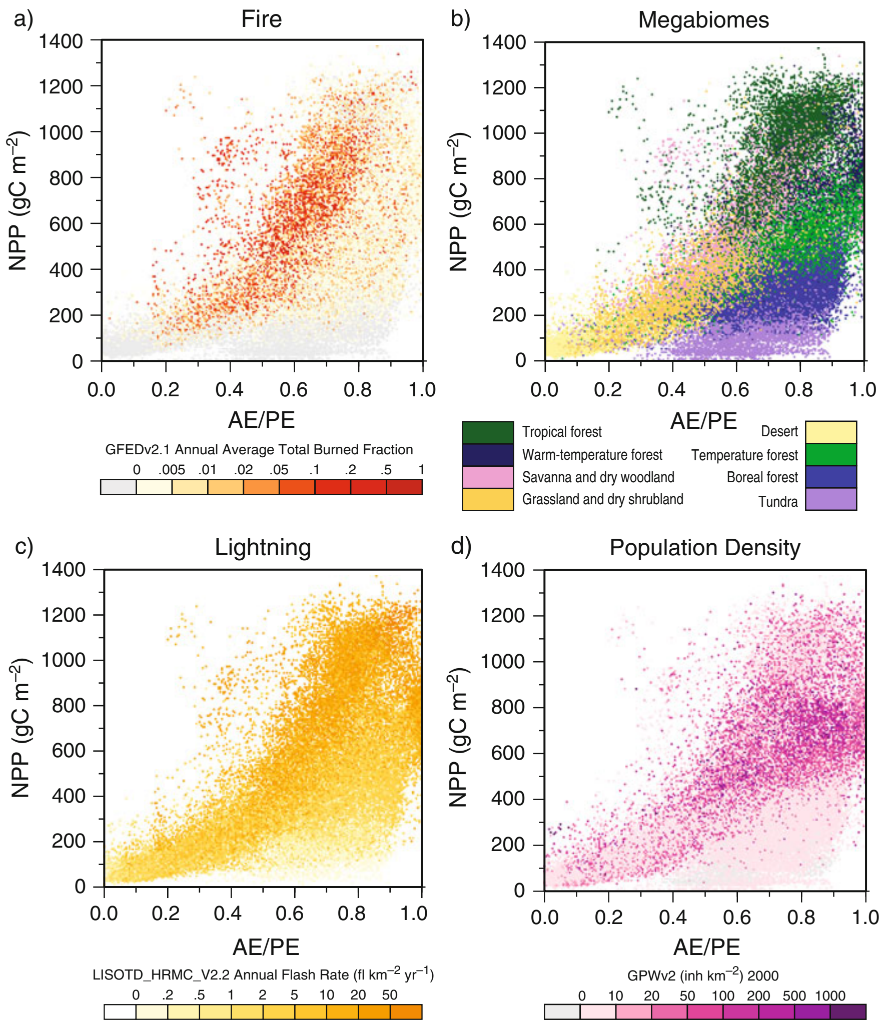

Fig. 4 Theoretical relationships between climate, lightning, vegetation, population density, and fire at a global scale based on satellite remotely sensed burnt-fraction data (GFEDv2.1) (van der Werf et al., 2006). Model-based estimates of net primary productivity (NPP) are from Cramer et al. (1999); values of actual to equilibrium evapotranspiration (AE/PE) were calculated using the CRU CL 2.0 data set (New et al., 2002). The distribution of biomes is plotted in climate space for comparison. Lightning data are from the LIS/OTD HRMC V2.2 dataset (http://gcmd.nasa.gov/records/GCMD_lohrmc.html) and population density from the HYDE 3.0 data set (Klein Goldewijk and van Drecht, 2006)

many areas, fire is uncommon at both very low and very high population densities (Archibald et al., 2009).

A conceptual model of the major controls on fire must include climate, vegetation, and human activity (e.g., Lafon and Grissino-Mayer, 2007; Balshi et al., 2007; Krawchuk et al., 2008). Climate controls fire activity through changes in fire weather, which include factors such as temperature, precipitation, wind, and the length of dry spells between storms, all of which show complex geographic variation. Fire weather also determines the occurrence of natural ignitions through lightning. Vegetation regulates fire because its composition and structure determine fuel characteristics (amount and flammability). Net primary productivity (NPP), for example, is a strong predictor of fire occurrence (Krawchuk and Moritz, 2009). However, at broad spatial scales and on multi-annual timescales, vegetation type and productivity are themselves determined by climate. Topography is a secondary control on fire that strongly influences fire behavior at finer spatial and temporal scales (Heinselman, 1973; Gavin et al., 2006; Parisien and Moritz, 2009). The atmosphere and soil link fire effects back to fire controls through feedback processes (e.g., via trace gas and aerosol emissions and via nutrient supplies that affect vegetation productivity). Fuels, ignitions, and fire weather are proximate determinants of fire that are themselves determined by vegetation, climate, and human activities.

People and Fire

There is a long and varied history of interactions between people and fire (Pyne, 1995; Pausas and Keeley, 2009). The interpretation of this history has often been the subject of controversy, and much of the debate is informed more by perception than observation.

People can alter fire regimes directly both by lighting fires, either deliberately or accidentally, and by excluding or suppressing fires. Available data suggest that people are responsible for igniting the largest *number* of fires today (FAO, 2007), except in boreal forests where lightning is still the primary ignition source. In southeast Asia, northeast Asia, and South America, where fire is used extensively for land clearance and the maintenance of pasture and agricultural lands, people are estimated to light over 80% of all fires (FAO, 2007). In the western US, about half of all fires – and almost all fires that occur during the winter – are ignited by people (Bartlein et al., 2008) (Fig. 5a, b and c); however, more fires are started by lightning during the summer fire season, and lightning-ignited fires account for most of the *area* burnt (Kasischke et al., 2006). This appears to be a common pattern: although people have a strong impact on the number of fire starts, they have a much smaller impact on the amount of vegetation burnt, and thus comparatively little influence on the magnitude of fire-induced changes in the Earth system.

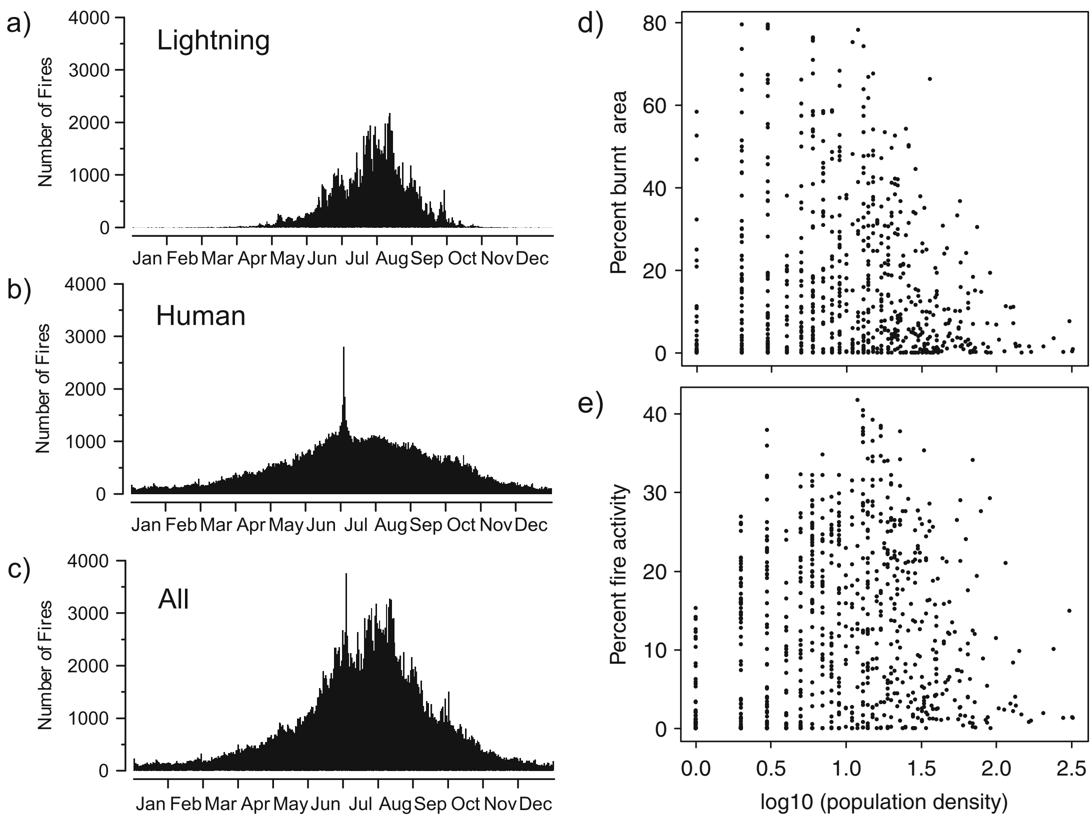

Fig. 5 The influence of people on key aspects of fire regimes. Number and timing of fires caused by **a** lightning, and **b** humans compared to **c** total fires in the western USA (redrawn from Bartlein et al., 2008). Percent **d** burnt area and **e** fire activity (number of fires) as a function of population density in South Africa (redrawn from Archibald et al., 2009)

The high economic and social costs of fires have led to active policies of fire suppression in many countries (FAO, 2007). The impacts of fire suppression, however, are not always as intended. The exclusion or suppression of fire has been claimed to contribute to dangerous fuel build-up (Donovan and Brown, 2007; Mitchell et al., 2009), changes in forest stand structure (including a paradoxical reduction in carbon storage: Fellows and Goulden, 2008), undesirable changes in species composition, and pest and disease outbreaks (Castello et al., 1995). Fires that do occur in areas where fire has been suppressed by fire fighting can burn larger and hotter, and thus become increasingly destructive rather than restorative (Moritz and Stephens, 2008).

People also have an indirect but important impact on fire regimes, through altering land use (e.g., Heyerdahl et al., 2001; Marlon et al., 2008; Carcaillet et al., 2009; Krawchuk and Moritz, 2009). Similar changes in land use do not necessarily have the same effect in different ecosystems. Evidence from South America indicates reductions in fire occurrence associated with increased grazing in prairies and savannas, but increases in fire are associated with increased grazing in rain forests (Bella et al., 2006). In fire-sensitive regions, such as in seasonally dry tropical forests, the effects of human "deforestation" fires are well known. Large fires are novel to these ecosystems (Cochrane et al., 1999; Bush et al., 2007a; Bush et al., 2007b; Field et al., 2009), and there is concern about the effects of such fires on ecosystem services and biodiversity (Cochrane and Barber, 2009).

The pervasive use of fire by people have led some modellers to estimate past fires and emissions by scaling changes in fire to changes in population growth (e.g., Dentener et al., 2006). Fire data from South Africa, however, indicate that population density is not linearly related to burnt area or number of fires (Archibald et al., 2009). Instead, burnt area was found to be inversely correlated with changes in population density; burnt area declines very slightly at low levels and then more rapidly declines as densities increase further (Fig. 5d). Numbers of fires increase with population density at low levels, but then decreases as population density continues to rise (Fig. 5e). Temporal trends in fire history at the global scale show a similar correlation between increasing population levels and increasing biomass burnt up to a certain level (i.e., when global population reached about 1.6 billion at 1900 AD) followed by a rapid reduction in fire activity as global population grew from 1.6 to over 6 billion in 2000 AD, significantly reducing the "available habitat" for fire through land-use changes (Marlon et al., 2008).

Fire and Vegetation Dynamics

Wildfire is an agent of vegetation disturbance, initiating succession and promoting short-term changes in biogeochemical cycling (Liu et al., 2005). Fire also shapes population dynamics and interactions (Mutch, 1970; Biganzoli et al., 2009). In the short-term, smoke haze from large-scale fires reduce light availability sufficiently to noticeably decrease photosynthesis (Schafer et al., 2002) and thus potentially jeopardize the yield of annual species and crops. Paleoecological data shows that changes in fire regime associated with rapid climate changes have lead to abrupt reorganizations of vegetation communities (Shuman et al., 2002; Williams et al., 2008). Abrupt changes in fire regimes associated with the relatively recent human colonization of regions such as New Zealand appear to have promoted large-scale and permanent changes in vegetation (McGlone and Wilmshurst, 1999; McWethy et al., 2009). Similarly, the use of fire for deforestation in tropical forests or the introduction of invasive grasses in the more recent past have led to the conversion of forests and woodlands to more open, flammable communities (D'Antonio and Vitousek, 1992; Cochrane et al., 1999). In tropical rainforests, deforestation fires initiate a positive feedback cycle, whereby fire creates canopy openings, leading to reduced fuel moisture and low relative humidity and hence increasing the risk of fire (Cochrane et al., 1999; Nepstad et al., 2004). In contrast, fires in arid regions can destroy vegetation cover and fuel continuity and prevent a recurrence of fire until the system recovers. Increases in human-caused ignitions can increase fire frequency beyond the range of natural variability thereby altering species composition and decreasing soil fertility (Tilman and Lehman, 2001; Syphard et al., 2009). Deliberate protection from fire promotes the growth of closed forests. In some regions, these changes in vegetation lead to changes in the type, intensity and frequency of fires. For example, regrowth of forests after fire exclusion leads to a switch from frequent, low-intensity surface to less frequent but high-intensity crown fires (Allen et al., 2002). Local circumstances that exclude fire may favour the persistence of fire-sensitive vegetation types, such as tropical rainforest, such that the occurrence or absence of fire may be responsible for alternate stable ecosystems within the same climate zone (Grimm, 1984; Wilson and King, 1995; Bowman, 2000).

Many species possess survival or reproductive traits that allow them to persist in fire-prone areas (Bond and van Wilgen, 1996; Schwilk and Ackerly, 2001; Pausas et al., 2004; Paula et al., 2009). The development of thick bark, for example, allows trees to survive low-intensity fires, while epicormic resprouting after damage favours rapid regrowth after fire. The association of plant species with distinct reproductive and survival characteristics under different fire regimes suggests that fire is a powerful biological filter on plant distribution, and has led to speculation that fire has had a pronounced evolutionary effect on the development of biotas. It has been suggested that the expansion of savannas around 7–8 million years ago, for example, was a result of increases in wildfire that led to a drier climate through biophysical and biogeochemical feedbacks to climate, and thus promoted expansion of drought-tolerant vegetation (Beerling and Osborne, 2006). Similar arguments have been made for the aridification of Australian vegetation following aboriginal colonization ca. 45–50 thousand years ago (Miller et al., 1999), although in this case there is evidence for similar changes in fire regime in regions not colonized until much later (Dodson et al., 2005; Stevenson and Hope, 2005) and the observed aridification can be explained by external forcing alone (Hope et al., 2004; Pitman and Hesse, 2007). Traits that promote fire or recovery following fire are not unambiguously the result of natural selection by fire (Schwilk and Kerr, 2002), and both the expansion of savannas and drought-tolerant vegetation at various stages in Earth's history is susceptible to a more direct climatic explanation.

Potential Feedbacks to Climate

Changing climate and human activities lead to change in fire regimes, but wildfires could in principle themselves contribute to changes in climate – via emissions of long-lived greenhouse gases (CO_2, CH_4, N_2O), other trace gases including biogenic volatile organic compounds (BVOCs), and aerosol precursors, and physical land-surface changes resulting from changes in vegetation structure induced by fire (Galanter et al., 2000; Winkler et al., 2008; DeFries et al., 2008). Disentangling the relative importance of different putative feedbacks among vegetation, fire, and climate is challenging (Bonan, 2008) and represents an area of Earth System Science that remains poorly quantified.

Carbon Cycle Feedbacks

Fires consume vast quantities of vegetation annually and in the process release carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), and nitrous oxide (N_2O) (Cofer et al., 1998; Rinsland et al., 2006; Bian et al., 2007), which are primary, long-lived greenhouse gases (Fig. 6). Terrestrial biomass represents about a quarter to a third of the terrestrial carbon reservoir (Field and Raupach, 2004; Houghton et al., 2009). Biomass burning for deforestation is estimated to have contributed ca. 19% of the atmospheric CO_2 increase since pre-industrial times (Randerson et al., 1997; Bowman et al., 2009). Annually, fires release about 2.5 Pg of carbon per year (Pg C/year) to the atmosphere (Lavoué et al., 2000; van der Werf et al., 2006; Schultz et al., 2008). This amount is larger during severe drought years (van der Werf et al., 2004; van der Werf et al., 2006). During the 1997–1998 El Niño, burning in Indonesia alone contributed about 40% of all carbon emitted globally that year, which showed the largest annual increase in CO_2 since precise records began in 1957 (Page et al., 2002). The trend toward increasing fires in Indonesia and in the tropical Americas is mainly attributed to deforestation fires (Morton et al., 2008; Field et al., 2009), but climate-induced increases in droughts are expected to exacerbate the problem (van der Werf et al., 2008a; Cochrane and Barber, 2009).

Fire emissions of CO_2 add to the global atmospheric CO_2 budget when more carbon is added than is sequestered by vegetation regrowth (Fig. 6). As a result, fires in savanna and grassland ecosystems, for example, where post-fire vegetation recovery is rapid, have no net effect on the atmospheric CO_2 budget in the absence of a fire-regime shift. When post-fire vegetation recovery is slower as in temperate or boreal forests, CO_2 emissions may have long-lasting effects

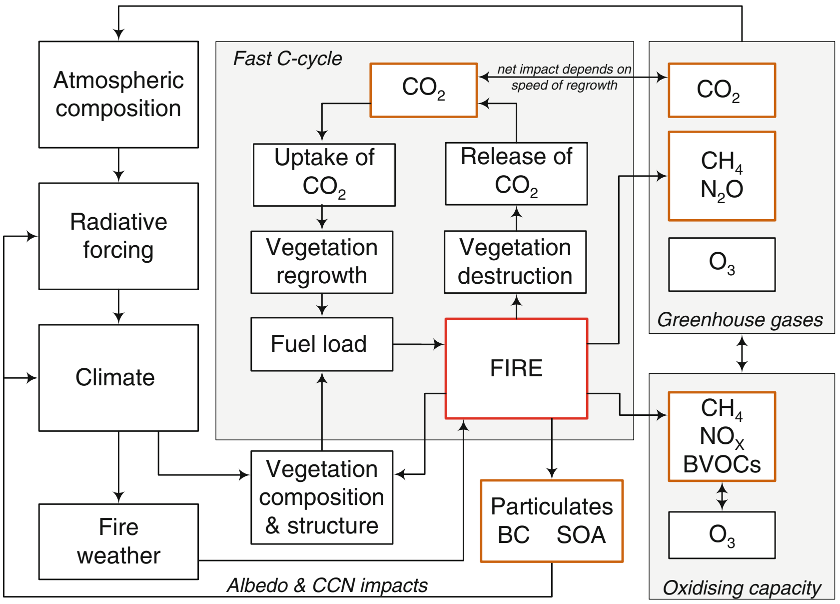

Fig. 6 Schematic showing carbon-cycle, atmospheric chemistry and biogeophysical feedbacks from fire to the climate system

(Amiro et al., 2001; Litvak et al., 2003; Balshi et al., 2009). Fire is becoming an increasing concern in boreal and tundra regions in particular because of the high sensitivity of these ecosystems to global warming. Increased surface heating from higher fire frequencies in tundra ecosystems associated with rapid warming there could contribute to the release of large quantities of carbon from melting permafrost (Zoltai, 1993; Mazhitova, 2000) increased fire activity in boreal forests has the potential to significantly increase carbon emissions there (Kasischke et al., 1995; Kasischke and Bruhwiler, 2002; Flannigan et al., 2005).

Atmospheric Chemistry Feedbacks

The main atmospheric impacts of fire (Fig. 6) are related to emissions of particles, nitrogen oxides (NO_x), methane (CH_4), and other volatile hydrocarbons, either directly or through secondary effects including the formation of ozone (O_3) and aerosols (Andreae and Merlet, 2001). Methane is 25 times more powerful than CO_2 as a greenhouse gas, but has a shorter atmospheric lifetime. Biomass burning is only one source of CH_4; emissions from wetlands and agricultural activities are larger. Bowman et al. (2009) estimate that biomass burning from deforestation fires currently contributes about 4% to the current total radiative forcing of CH_4 (Fig. 7). However, there is substantial uncertainty regarding the contribution of biomass burning to variations in CH_4, owing to the variety of methane sources. Furthermore, the interannual variability of global CH_4 concentrations is not well understood.

Attempts have been made to disentangle the relative importance of contributing factors to past changes in atmospheric composition as shown in ice core

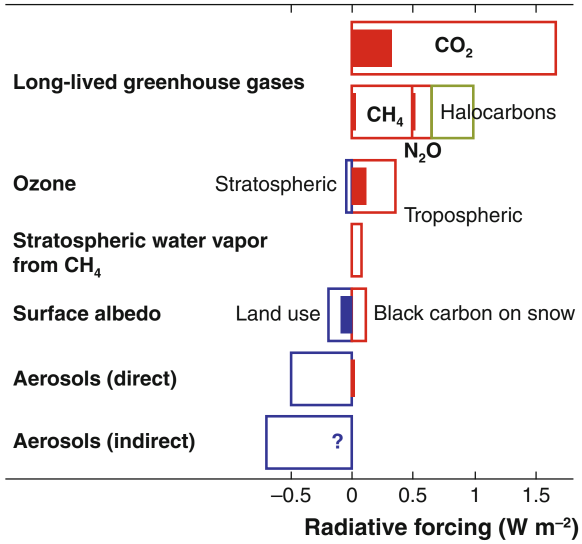

Fig. 7 Estimated contribution of changes in fire regime due to deforestation to radiative forcing over the industrial era, redrawn from Bowman et al. (2009)

records through paleoreconstructions and modeling experiments (Ferretti et al., 2005; Fischer et al., 2008; Houweling et al., 2008). Thonicke et al. (2005) simulated changes in biomass burning at the Last Glacial Maximum (LGM) compared to pre-industrial conditions using a Dynamic Global Vegetation Model with an explicit simulation of fire processes. In this simulation, reduced biomass burning at the LGM resulted in ca. 1 Pg less carbon released annually to the atmosphere than under pre-industrial conditions, and concomitant reductions in other pyrogenic emissions. Assuming constant atmospheric lifetimes of these gases, the reduction in pyrogenic CH_4 and N_2O emissions would be equivalent to a change in radiative forcing of ca. –0.2 W/m^2 in both cases, which is 7 and 8.5%, respectively, of the overall change in radiative forcing associated with the total LGM to pre-industrial change in the concentrations of these two gases. The possible impact of reduced pyrogenic emissions of CO_2 at the LGM on the glacial-interglacial change in atmospheric CO_2 concentration is negligible, compared to the large uptake of CO_2 by the land biosphere during the deglaciation and the even larger release of CO_2 by the ocean. However, changes in pyrogenic emissions could have had further minor impacts on radiative forcing through influencing ozone production and atmospheric oxidizing capacity, with implications, e.g., the lifetime of CH_4 (Thonicke et al., 2005).

Nitrogen oxides (NO_x) other than N_2O and volatile organic carbons (BVOCs) from biomass burning contribute to the formation of ozone (O_3) in the troposphere. Global biomass burning emissions represent ca. 25% of the global NO_x emissions (Jaegle et al., 2005). Hastings et al. (2009) used ice core data to demonstrate that human activities have caused a rapid recent increase in NO_x. Tropospheric O_3 is a greenhouse gas. Bowman et al. (2009) estimate that biomass burning for deforestation has contributed about 17% to forcing due to tropospheric O_3 during the industrial period (Fig. 7). At ground level, ozone is also a pollutant that reduces air quality, affects human health, and damages vegetation and ecosystems. CO, NO_x, and BVOCs produced during wildfires can cause significant increases in local and regional ozone levels (Pfister et al., 2005; Winkler et al., 2008). Simulations have demonstrated substantial sensitivity of radiative forcing to variation in overall pyrogenic emissions and relative changes in warming (black carbon, BC) and cooling (secondary organic aerosol, SOA) aerosol (Ito et al., 2007; Naik et al., 2007).

Impacts of Soot

Fires affect land-surface albedo by altering vegetation cover, darkening land through soot (black carbon) deposition, and increasing snow exposure. Small-scale changes in land-surface albedo have very little effect on the global radiative budget (Randerson et al., 2006) and in any case the impacts of these changes persist for only a short time until the ecosystems begin to recover. The impact of soot production on atmospheric chemistry may be a more important influence. Soot aerosols from biomass burning can affect regional climate by absorbing radiation and heating the air (Fig. 6); this in turn can alter regional atmospheric stability and vertical motions, and thus influence large-scale circulation and the hydrologic cycle (Menon et al., 2002). Open biomass burning associated with deforestation and crop residue removal produces ~40% of global black carbon emissions (Bond et al., 2004). Indirect effects on radiative forcing occur primarily because aerosols affect cloud properties (Sherwood, 2002; Guyon et al., 2005). Unlike trace gases, aerosols are not well mixed: aerosol distribution is heterogeneous spatially and through the atmospheric column vertically. As a result, the effects of aerosols on climate are difficult to model and remain one of the largest uncertainties in the simulation of global climate. Bowman et al. (2009) estimate a slight negative forcing from direct aerosol effects from biomass burning but consider the indirect aerosol effects too uncertain to estimate (Fig. 7).

Emissions of soot from wildfires decrease the albedo of snow, ice, and land and thus can increase surface temperatures (Hansen and Nazarenko, 2004). Increasing concentrations of black carbon, in combination with decreasing concentrations of sulfate aerosols, have substantially contributed to rapid Arctic warming during the past three decades (Shindell and Faluvegi, 2009). Additionally, black carbon within soot that is deposited over snow and ice significantly increases solar absorption and melting (Ramanathan and Carmichael, 2008), which may be one of the important contributors to Arctic sea ice retreat (Flanner et al., 2007). The impact of even small shifts in albedo on snow has large potential consequences for radiative forcing due to positive feedbacks. Koch and Hansen (2005) used a global climate model to show that soot in the Arctic today comes from both industrial combustion and biomass burning. Model experiments indicate that soot has substantially contributed to rapid Arctic warming during the past three decades (Shindell and Faluvegi, 2009), and may be responsible for half of the 1.9ºC increase in Arctic temperatures between 1890 and 2007 because of its effects on snow and ice albedo at high latitudes (Ramanathan and Carmichael, 2008).

Costs

Fires in Indonesia during the 1997–1998 droughts brought the potential costs of uncontrolled wildfires to global attention (Tacconi, 2003). The fires were largely set to clear land for oil palm and timber plantations and affected about 5 million hectares. Smoke and haze from the burning peat and forest engulfed millions of people in Southeast Asia, reducing visibility, causing respiratory illness, and increasing infant mortality (Jayachandran, 2005). The economic costs were estimated at between US$4.4–9 billion – an amount that exceeds the funds needed annually to provide basic sanitation, water, and sewerage services to all of Indonesia's 120 million rural poor (EEPSEA and WWF, 1998). The fires have been widely regarded as the largest environmental disaster of the century (Glover, 2001).

The costs of these fires have been studied in detail (Tomich et al., 2004; Lohman et al., 2007). Costs related directly to suppression and control of the fires were less than 1% of the total costs (Fig. 8c). Direct losses incurred during and immediately after the fire event, including the costs of lost timber, agriculture, and tourist revenue amounted to ca. 28% of the total cost. The less tangible indirect costs, which include direct forest benefits (i.e., food, local medicines, raw materials and recreation), indirect forest benefits (e.g., storm protection, water supply and regulation, erosion control, soil formation, nutrient cycling, and waste treatment), and costs associated with biodiversity losses, and the release of carbon to the atmosphere, were estimated as comprising the largest (ca. 48%) economic impact (Fig. 8c) while short-term health costs were estimated as ca. 23% of the total cost. Although this accounting appears comprehensive, there are large uncertainties associated with the estimates of indirect costs. The indirect costs associated with carbon release and biodiversity loss, for example, reflect income lost to Indonesia for conserving its forest; but these are hypothetical, being estimated as the price that agencies and organizations are willing to pay to conserve tropical forests (EEPSEA and WWF, 1998). On the other hand, additional costs associated with evacuations, long-term health damages or loss of life, or effects from the haze that may have reduced crop productivity, photosynthesis, pollination, and other biological processes (see e.g., Schafer et al., 2002), were not taken into account. The estimated biodiversity costs do not take into account the intrinsic value of species that have been extirpated or whose extinction has been accelerated, the potential but currently unexploited value of ecotourism or medicines, or losses of cultural diversity of indigenous forest-based culture (EEPSEA and WWF, 1998).

There are few reliable data on the cost of wildfires for many of the regions where fire is prevalent. Even in developed countries, data on fire-related costs are often uncertain and incomplete. According to the FAO global fire assessment (FAO, 2007), the direct costs of fire are in the hundreds of millions of dollars for many countries, and in the billions for larger countries and regions. India reported costs of US$107 million in one year, for example. Russia reported costs of US$4.2 billion in 1998, and timber losses were estimated at US$0.5–1 billion yearly in northeast Asia. Mexico estimated losses of US$337 million in wood, US$6.6 million in firewood and US$39 million in reforestation costs.

Wildfires are recognized as environmental disasters by the international community; this fact provides an alternative tool for the assessment of costs and impacts (International Disaster Database: http://www.emdat.be/). Fifteen countries declared wildfire disasters during the decade 2000–2009 (Fig. 8b). The predominance of countries with Mediterranean-type climates in this list reflects the strong control of climate on wildfires and points to the vulnerability of these environments to fire in the face of global warming. The analyses show large discrepancies in the overall cost of wildfires between countries. The estimated economic losses from wildfires in the USA dwarf the losses experienced by all of the other countries (Fig. 8a). However, when expressed

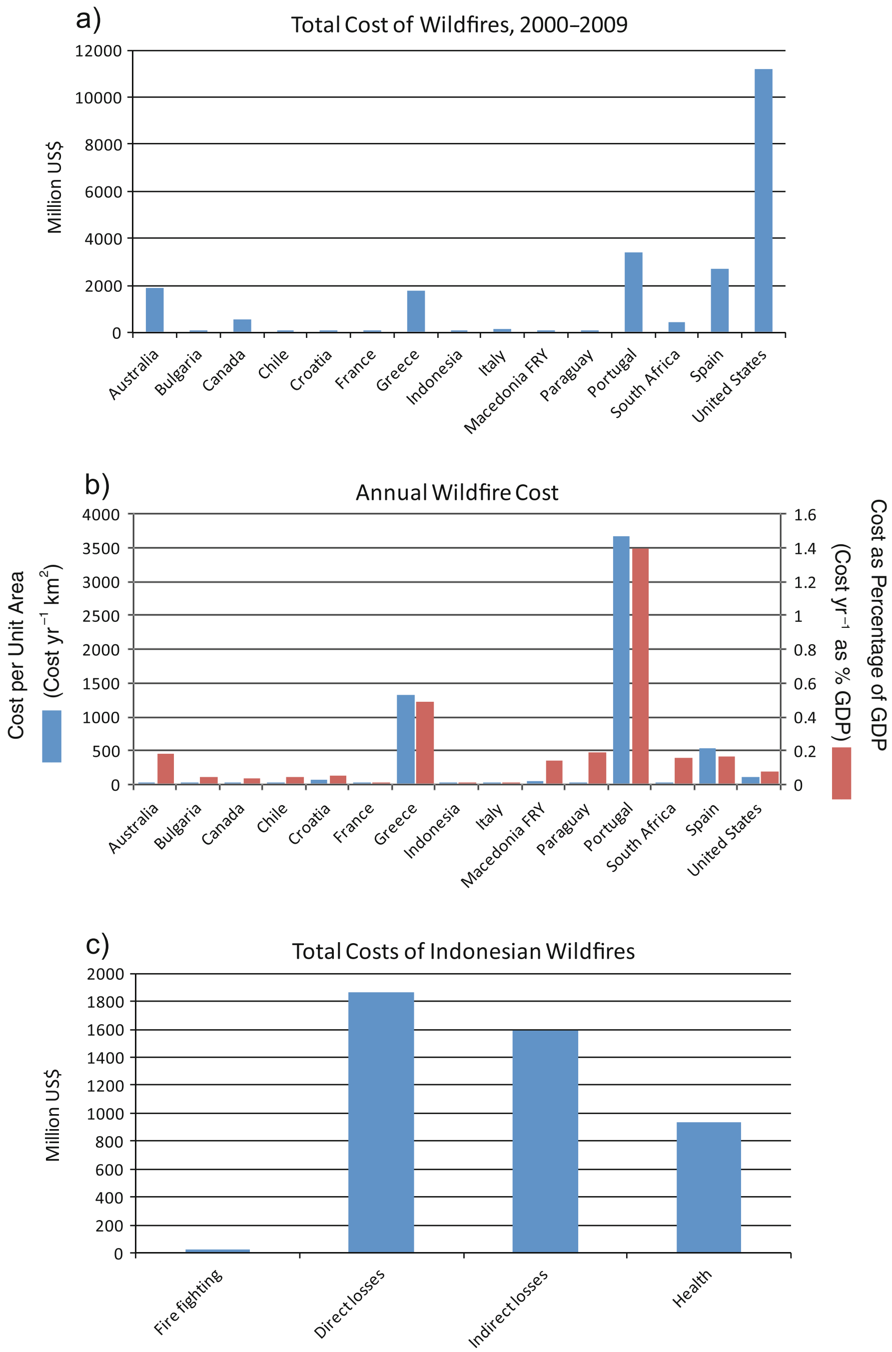

Fig. 8 The costs of wildfires. **a** Estimated costs of wildfire disasters in the decade 2000–2009 by country in millions of US$, where a wildfire disaster is defined as an event where more than ten people were killed or more than 100 injured, where a state of emergency was declared or international aid was solicited. Data from the International Disaster Database (http://www.emdat.be/). These costs are re-expressed **b** as a yearly cost per area where area is total land area of the country and as a percentage of gross domestic product (GDP) in 2008 (The World Bank: World Development Indicators database: http://web.worldbank.org/WBSITE/EXTERNAL/DATASTATISTICS/0,,menuPK:232599~pagePK:64133170~piPK:64133498~theSitePK:239419,00.html). **c** Estimated costs of the fires in Indonesia during the 1997/1998 ENSO season, showing fire-fighting costs, direct costs from loss of timber, agriculture or tourist revenue, indirect costs including ecosystem services provided by forests, indirect benefits from forest, carbon costs, and loss of biodiversity, and short-term health costs. Redrawn from data in Lohman et al. (2007)

either in terms of areal impact or as a proportion of gross national product (GDP), the economic impact of fire in the USA is much smaller than its impact in, e.g., Australia or several countries in southern Europe (Fig. 8b). The wildfire disasters in Portugal, in particular, cost the equivalent of 1.4% of GDP. This form of accounting does not include indirect costs, and the actual economic impact of wildfires may be much larger than these numbers suggest.

The fire-fighting costs for the Indonesian fires were US$ 34 million, or less than 1% of the total estimated costs. By comparison, the fire-fighting costs in the USA for the Yellowstone National Park fires of 1988 were US$ 120 million. After the "Black Saturday" fires in February 2009, the Australian government budgeted nearly US$ 1 billion for costs associated with fire-fighting, clean up, and rebuilding. Fire-fighting is a much larger and better-funded endeavor in developed countries such as the US and Australia, typically involving large hand-crews, tankers, bulldozers, helicopters, and airplanes to protect lives, homes, and structures even though a change in weather conditions is always, in reality, the main agency that stops large wildfires.

Fire suppression activities are relatively easy to quantify because they occur during and immediately after the fire event. Other direct costs, such as loss of property or timber are also relatively easy to assess (Dale, 2009). However, the longer-term, indirect consequences of fires have far-reaching effects that can dwarf the costs related to fire suppression. Long-term damages to watershed values and other ecosystem services, such as the regulation of water and soil quality and quantity, and of carbon sequestration, for example, may represent the most significant costs from large fire events (Lynch, 2004). The California Fire Plan delineates a comprehensive list of both cultural and environmental assets potentially at risk from wildfire in order to identify areas where the potential cost of a major wildfire event is largest, and thereby help prioritize pre-fire management activities. The asset analysis includes items such as air and water quality, hydropower generation, flood control, water storage capacity, historic buildings, and scenic areas. Areas are ranked based on the potential physical effects of fire as well as the human valuation of those effects.

A recent analysis estimated the total cost of fire in Australia at over US$7.7 billion per annum, or about 1.15% of the country's GDP (Ashe et al., 2009). Similar analyses show that total fire-related costs in the UK, USA, Canada, and Denmark all fall in the range of 0.9–2% of GDP. In the USA, fire-related costs are ca. 2% of GDP and rapidly increasing not only because of an increase in the number of big fires but because of rapid development of homes in the wildland-urban interface (USDA, 2006; Rasker, 2009). Ashe et al. (2009) have shown that Australia is investing about US$6.6 billion (or 85% of the total cost of fire) to manage a loss of about US$1.2 billion (or 15% of the total cost of fire). Such analyses raise critical questions about current approaches to fire management, in Australia and elsewhere.

Future Fire Regimes

Increases in the number of large fires and in the area burnt have been observed during recent years in many regions, including Canada (Stocks et al., 2002; Gillett et al., 2004), the United States (Westerling et al., 2006), southern Europe (Piñol et al., 1998), Siberia (Kajii et al., 2002), eastern Eurasia (Balzter et al., 2007; Groisman et al., 2007), and Australia (Cary, 2002). It seems increasingly likely that these increases are a result of anthropogenic climate changes (e.g., see Running, 2006), and this has led to a growing concern for predicting how potential changes in climate over the twenty-first century might affect natural fire regimes.

Most of the assessments of the impact of anthropogenic climate changes on regional wildfire regimes have been based on observed relationships between climate and some aspect of the fire regime at a regional or sub-continental scale (e.g., Flannigan et al., 2001; Cardoso et al., 2003; Balshi et al., 2009; Girardin and Mudelsee, 2008). Krawchuk et al. (2009) have used various statistical relationships to project future changes in fire regimes globally. Although they show major increases in the probability of fire in for example the boreal zone, this increase is offset by reductions in the incidence of fire elsewhere, and overall there is no discernible change in fire at the global scale. A key issue with all of these future predictions is the degree to which statistical relationships characteristic of modern fire-climate interactions hold under potentially different climates and CO_2 concentrations. Flannigan et al. (2001) addressed this by showing that application of the modern statistical relationship between fire weather and fire incidence to simulated climates for 6,000 years ago produced patterns of changes in fire regimes across Canada consistent with charcoal-based reconstructions of changes in biomass burning during the mid-Holocene. In general, however, there have been few attempts to test whether statistical relationships observed under modern conditions are likely to hold when climate changes beyond the modern observed range.

Process-based modeling provides a way of overcoming the limitations of statistical modeling. There are now many fire models, some adapted for specific ecosystems (e.g., Ito and Penner, 2005; Crevoisier et al., 2007) while others are global in scope (Lenihan et al., 1998; Kucharik et al., 2000; Thonicke et al., 2001; Venevsky et al., 2002). Some models have been designed to be coupled within climate models (e.g., Arora and Boer, 2005; Krinner et al., 2005) in order to investigate feedbacks. There have been only a few attempts to apply such models to estimate future changes in fire regimes either at a regional (Bachelet et al., 2005; Lenihan et al., 2008) or at a global scale (Scholze et al., 2006). Nevertheless, some robust features are beginning to emerge. In general, there is an overall increase in fire in response to warming over the twenty-first century (Fig. 9). Some regions, however, experience reduced fires: in tropical regions, this decrease reflects the fact that warming is accompanied by an increase in precipitation while in semi-arid regions the decrease occurs because regional warming results in considerable reduction of fuel loads and decreases in fuel connectivity. The changes in fire regimes, whether these are regional increases or decreases in fire, become more marked through the century (compare Fig. 9a, b, and c) and with the magnitude of the global increase in temperature (compare, e.g., Fig. 9c with f).

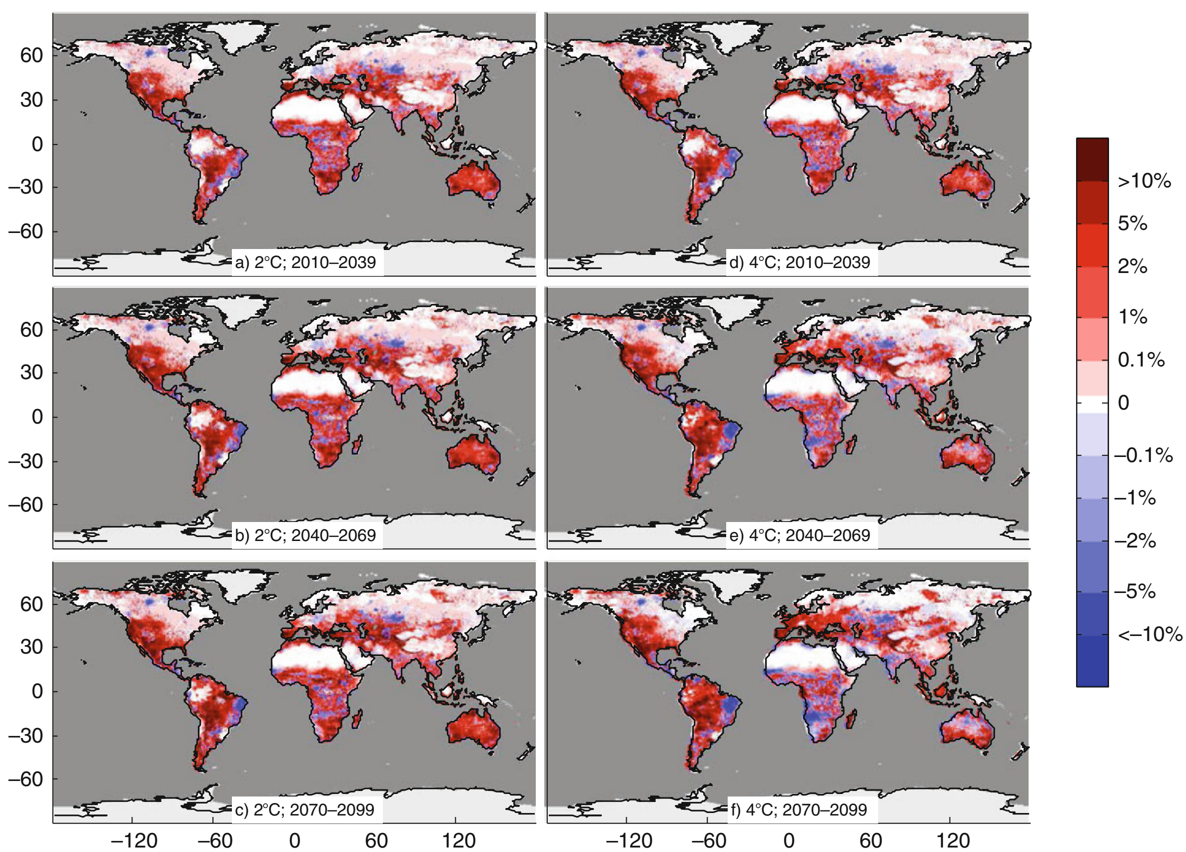

Fig. 9 Changes in global fire regimes during the twenty-first century as simulated by the coupled fire-vegetation model LPX (Prentice et al., in preparation) driven by output from the HADCM3 coupled climate model pattern-scaled to produce either a 2°C or a 4°C warming by 2050 (Harrison et al., in preparation)

The recognition that there will be regional differences in the direction of future changes in fire regime is common to both statistical and process-based modeling projections, as is the general idea that the changes in fire regime will become more severe during the twenty-first century. However, detailed comparisons of the predictions show few other similarities. Krawchuk et al. (2009) show increased fire across much of the boreal zone, whereas Scholze et al. (2006) show a decrease in fire in large parts of the boreal zone and major increases in fire in the temperate forests and in semi-arid regions. The simulations presented here (Fig. 9) show more extreme changes in fire regimes than either of these two previous studies. There is an urgent need to evaluate and improve approaches to predicting changes in future wildfires in response to anthropogenic climate changes, both because of the large costs and because of the potential feedbacks from fire to climate (Flannigan et al., 2009). It is also important because future climate changes could amplify direct human impacts on fire regimes in that human-set fires are more likely to escape control and to persist for longer during drought conditions (van der Werf et al., 2008b).

Prognostic modeling of fire is relatively new and there are, as yet, no model-based investigations of the potential magnitude of pyrogenic feedbacks through atmospheric chemistry to climate. It is difficult to estimate the overall impact of potential future changes in biomass burning on radiative forcing without targeted model experiments because the changes in biomass burning are regionally specific and the influence of changes in pyrogenic emissions on atmospheric chemistry are sensitive to location (Naik et al., 2007). Although Bowman et al. (2009) have suggested that deforestation fires during the industrial era were responsible for ca. 19% of the total increase in radiative forcing since pre-industrial times, Arneth et al. (in revision) have estimated that the additional net radiative forcing over the twenty-first century would be small, of the order of 0.02 W/m^2.

Mitigation and Adaptation: Can We Manage Future Fire?

The observed increases in large wildfires in recent decades, together with predictions of changes in regional fire regimes during the twenty-first century, raise urgent questions as to how fires should be managed. Policies geared toward the total suppression of wildfire are not tenable as a strategy for dealing with projected changes in fire regimes during the twenty-first century. Even in the most developed countries, fire-fighting capacity has been insufficient to deal with wildfires in recent years (Lohman et al., 2007; Bowman et al., 2009) and the costs of protection and fire-fighting continue to escalate (FAO, 2007). There is also increasing awareness of the deleterious effects of fire suppression, and particularly of the fact that fire suppression may lead to bigger and more devastating fires through the build-up of dangerous levels of fuel (Dombeck et al., 2004; Lynch, 2004). However, even when property is not at risk and there are obvious benefits to be gained from letting fires burn naturally, existing incentives, policy restrictions, and personnel limitations can overwhelmingly predispose institutions to continue to suppress fires (USDA, 2006).

The impact of fire suppression can be seen in the contrasting histories of recent fire in Arizona (Skroch and Swetnam, 2008). As a result of a change in management policy, lightning-ignited fires have been allowed to burn in the Rincon Mountains of Saguaro National Park since 1983. The forests now contain more mature trees and less understory fuels. However, fire-suppression policy still remains the policy in the more populated Santa Catalina Mountains nearby. As a result, build-up of fuel helped promote high-intensity crown fires which swept through the Catalinas in the summer of 2008, destroying hundreds of homes and costing millions of dollars to extinguish.

Fire suppression, and indeed controlled burning to some extent, may have a deleterious impact on biodiversity (Gill et al., 1999; Brown and Smith, 2000; Granström, 2001; Tilman and Lehman, 2001; Hutto, 2008). Many plant species are fire tolerant, require fire for regeneration, or promote fire as a competitive strategy (Bond and Midgley, 1995; Whelan, 1995; Schwilk and Ackerly, 2001). Savanna ecosystems, which occupy ca. 20% of the land surface, support a large proportion of the world's human population and most of its rangeland, livestock, and wild herbivore biomass (Scholes and Archer, 1997; Grace, 2006). Most savannas only exist as a result of fire (Bond, 2008; Lehmann et al., 2008). Thus, preserving natural fire regimes may be a necessary component of biodiversity management in the future (Shlisky et al., 2007; Hutto, 2008).

Reducing the risk of large wildfires through controlled burning (Pyne et al., 1996; Fernandez and Botelho, 2003) is increasingly seen as a management option in many parts of the world. Initiatives such as Firescape in southeast Arizona and the Four Forests Initiative on the Mogollon Rim, for example, are coordinating fire and fuel reduction activities at the landscape scale (Skroch and Swetnam, 2008). For such initiatives to be effective, however, the public needs to accept more frequent (albeit less destructive) fires despite the inherent risks associated with implement controlled burns and the inconvenience of smoke.

Controlled burning has also been proposed as a climate-change mitigation strategy (Myneni et al., 2001). Wildfires release substantial amounts of carbon. Bushfires in the savanna areas of northern Australia, for example, result in the loss of ca. 340,000 km^2 of vegetation annually and produce between 2 and 4% of Australia's accountable greenhouse gas emissions (Russell-Smith et al., 2007; Cook and Meyer, 2009). Similarly, the amount of CO_2 emitted by fires in the USA is equivalent to 4–6% of anthropogenic emissions at the continental scale (Wiedinmyer and Neff, 2007). It is not surprising, then, that the idea that mitigation of wildfire impacts through prescribed burning could potentially lead to major abatement in pyrogenic emissions has been discussed in the context of forests in Australia (Williams et al., 2004; Bushfire Cooperative Research Centre, 2006; Beringer et al., 2007), Europe (Narayan et al., 2007), and North America (Hurteau et al., 2008). The underlying idea is that prescribed burning decreases both the intensity and extent of subsequent wildfires by reducing fuel loads. Decreasing the intensity of fires, particularly in savannas, means that biomass is lost through decomposition rather than combustion, resulting in reduced emissions of CH_4 and N_2O. In savannas, prescribed burning in the early dry season, even though it may not affect the total area burnt, has nevertheless been shown to reduce emissions by reducing average fire intensity (Williams et al., 2002). On the other hand, low intensity (incomplete) burns may actually release more methane than intense complete burns (Crutzen and Andreae, 1990; Hao and Ward, 1993). Prescribed fire has been used successfully in northern Australia to achieve greenhouse-gas emission abatement (Russell-Smith et al., 2007). However, in general the magnitude of any reduction in emissions through fire management and prescribed burning is dependent on the nature of the vegetation and its dynamics, carbon stocks and flows, the efficacy of prescribed burning and the trade-offs between the different fire regimes. The gains in terms of climate-change abatement are probably small unless prescribed burning is useful to achieve other land-management goals. Indeed, many countries have already decided not to use fire management as a climate-change mitigation strategy because current agreements do not account for or protect against future changes in natural disturbances whether by fire or fire-promoted insect attack (Kurz et al., 2008). Additional agreements would be required to encourage the inclusion of forest management practices as a mitigation strategy.

Perhaps the most urgent aspect of future fire management concerns the reduction of economic damage. Part of the escalating cost of fire management has resulted from expansion of housing and urban infrastructure in inappropriate areas (i.e., adjacent to potentially lethal fire regimes) such as the wildland-urban interface in fire-prone ecosystems (van Wagtendonk, 2007). In many cases, people moving into such areas are unaware of the wildfire risk and are unprepared for it. The adoption of strategies to promote fire preparedness, such as creating defendable space around homes and other structures by clearing brush and keeping tree branches trimmed above the ground, using fire-proof building materials, and developing evacuation plans (Dombeck et al., 2004), only provide a limited solution to the fire management problem. The two primary options in addressing development in the wildland-urban interface are to deforest areas to remove the threat of fire, or to avoid development in such locations. In either case, a change in fire policy and management is becoming increasingly urgent as all indicators suggest that wildfires will continue to burn larger, hotter, and longer for the near future in such fire-prone ecosystems. At local scales, human values, about fire are at the root of many of our most serious fire-related problems. Issues such as the social, economic, and environmental impacts of fire and fire suppression, public safety, smoke, hazard mitigation, and fire communication and education must be examined within the mesh of political, social, and economic contexts where they exist (Gill, 2005). However, instituting policies that promote increased fire use in locations with risk to private property, such as cost/benefit analyses that aim to balance community and ecosystem needs and redesigning urban growth plans (Moritz and Stephens, 2008) are often considered politically infeasible (USDA, 2006).

The growing number, severity, and cost of fires in recent decades across all latitudes and countries have made it clear that governments and institutions are unable to adequately manage fire (FAO, 2007; Lohman et al., 2007). Networks of organizations have taken on increasing responsibilities for disaster policy design and administration, but their capacity is mixed, and most lack the ability to assess risk and evaluate their own activities (Charles and Michael, 2009). Models of successful fire-management strategies exist in some areas (Arno and Fiedler, 2004), and some of these models may be applicable in broader contexts. However, investment is needed in identifying others, and in documenting existing efforts so that we can learn from them.

Conclusions

Although highly variable in space and time, in general fire is tightly linked to climate and climatic variations. Global changes of the twenty-first century make it inevitable that the impact of large fires will continue and increase in magnitude. Changing patterns of wildfire activity present significant environmental, economic, and political challenges to communities and nations. At the core of these challenges is a need to increase public awareness of and political support for restoring fire to ecosystems that need it, to protect environments from fire only where fire is not needed or wanted, and to form new relationships with fire in an uncertain future. Adapting to climate change impacts on wildfire will require greater emphasis on flexible, adaptable approaches to fire management. New strategies may be required that acknowledge the limitations of fire-fighting capabilities and consequently focus on avoidance rather than attack. A greater emphasis on fire preparedness will also involve a shift in responsibility for creating defensible space to those who benefit most from fire protection services.

References

Allen CD, Savage M, Falk DA, Suckling KF, Swetnam TW, Schulke T, Stacey PB, Morgan P, Hoffman M, Klingel JT (2002) Ecological restoration of southwestern ponderosa pine ecosystems: A broad perspective. Ecol Appl 12:1418–1433.

Amiro BD, Todd JB, Wotton BM, Logan KA, Flannigan MD, Stocks BJ, Mason JA, Martell DL, Hirsch KG (2001) Direct carbon emissions from Canadian forest fires 1959–1999. Can J For Res 31:512–525.

Andreae MO, Merlet P (2001) Emission of trace gases and aerosols from biomass burning. Glob Biogeochem Cycles 15:955–966.

Archibald S, Roy DP, van Wilgen B, Scholes RJ (2009) What limits fire? An examination of drivers of burnt area in Southern Africa. Glob Chang Biol 15:613–630.

Arneth A, Harrison SP, Zaehle S, Tsigaridis K, Menon S, Bartlein PJ, Feichter H, Korhola A, Kulmala M, O'Donnell D, Schurgers S, Sorvari S, Vesala T (in revision) Terrestrial biogeochemical feedbacks in the climate system. Nat Geosci.

Arno SF, Fiedler CE (2004) Mimicking Nature's Fire: Restoring Fire-Prone Forests in the West (242 pp). Washington, DC: Island Press.

Arora VK, Boer GJ (2005) Fire as an interactive component of dynamic vegetation models. J Geophys Res 110:1–20.

Ashe B, McAneney KJ, Pitman AJ (2009) Total cost of fire in Australia. J Risk Res 12:121–136.

Atahan P, Dodson JR, Itzstein-Davey F (2004) A fine-resolution Pliocene pollen and charcoal record from Yallalie, southwestern Australia. J Biogeogr 31:199–205.

Bachelet D, Lenihan J, Neilson R, Drapek R, Kittel T (2005) Simulating the response of natural ecosystems and their fire regimes to climatic variability in Alaska. Can J For Res 35:2244–2257.

Balshi MS, McGuire AD, Duffy P, Flannigan M, Kicklighter DW, Melillo J (2009) Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st century. Glob Chang Biol 15:1491–1510.

Balshi MS, McGuire AD, Zhuang Q, Melillo J, Kicklighter DW, Kasischke E, Wirth C, Flannigan M, Harden J, Clein JS, Burnside TJ, McAllister J, Kurz WA, Apps M, Shvidenko A (2007) The role of historical fire disturbance in the carbon dynamics of the pan-boreal region: A process-based analysis. J Geophys Res 112:G02029.

Balzter H, Gerard F, Weedon G, Grey W, Combal B, Bartholome E, Bartalev S, Los S (2007) Coupling of vegetation growing season anomalies with hemispheric and regional scale climate patterns in Central and East Siberia. J Clim 20:3713–3729.

Bartlein P, Hostetler SW, Shafer SL, Holman JO, Solomon AM (2008) Temporal and spatial structure in a daily wildfire-start data set from the western United States (1986–96). Int J Wildland Fire 17:8–17.

Beerling DJ, Osborne CP (2006) The origin of the savanna biome. Glob Chang Biol 12:2023–2031.

Belcher CM, McElwain JC (2008) Limits for combustion in low O_2 redefine paleoatmospheric predictions for the Mesozoic. Science 321:1197–1200.

Bella CM, Jobbágy EG, Paruelo JM, Pinnock S (2006) Continental fire density patterns in South America. Glob Ecol Biogeogr 15:192–199.

Beringer J, Hutley L, Tapper N, Cernusak L (2007) Savanna fires and their impact on net ecosystem productivity in North Australia. Glob Chang Biol 13:990–1004.

Berner RA (1999) Atmospheric oxygen over Phanerozoic time. Proc Natl Acad Sci 96:10955–10957.

Bian H, Chin M, Kawa SR, Duncan B, Arellano A, Kasibhatla P (2007) Sensitivity of global CO simulations to uncertainties in biomass burning sources. J Geophys Res Atmos 112. doi: 23310.21029/22006JD008376.

Biganzoli F, Wiegand T, Batista WB (2009) Fire-mediated interactions between shrubs in a South American temperate savannah. Oikos 118:1383–1395.

Bird MI, Cali JA (1998) A million-year record of fire in sub-Saharan Africa. Nature 394:767–769.

Bird MI, Cali JA (2002) A revised high-resolution oxygen-isotope chronology for ODP-668B: Implications for Quaternary biomass burning in Africa. Glob Planet Change 33:73–76.

Bonan GB (2008) Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. Science 320:1444–1449.

Bond WJ, Midgley JJ (1995) Kill thy neighbour — an individualistic argument for the evolution of flammability. Oikos 73:79–85.

Bond WJ, van Wilgen BW (1996) Fire and Plants (263 pp). London: Chapman & Hall.

Bond T, Streets D, Yarber K, Nelson S, Wo J-H, Klimont Z (2004) A technology-based global inventory of black and organic carbon emissions from combustion. J Geophys Res 109. doi: 10.1029/2003JD003697.

Bond WJ, Keeley JE (2005) Fire as a global 'herbivore': The ecology and evolution of flammable ecosystems. Trends Ecol Evol 20:387–394.

Bond WJ (2008) What limits trees in C_4 grasslands and savannas? Annu Rev Ecol Evol Syst 39:641–659.

Bowman DMJS (2000) Australian Rainforests: Islands of Green in a Land of Fire (344 pp). Cambridge: Cambridge University Press.

Bowman DMJS, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, D'Antonio CM, DeFries RS, Doyle JC, Harrison SP (2009) Fire in the Earth system. Science 324:481–484.

Brown JK, Smith JK (2000) Wildland Fire in Ecosystems: Effects of Fire on Flora (p. 257). Gen. Tech. Rep. RMRS-GTR-42-vol. 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Brown KJ, Hebda RJ (2002) Origin, development, and dynamics of coastal temperate conifer rainforests of southern Vancouver Island, Canada. Can J For Res 32:353–372.

Bush MB, Listopad MCS, Silman MR (2007a) A regional study of Holocene climate change and human occupation in Peruvian Amazonia. J Biogeogr 34:1342–1356.

Bush MB, Silman MR, de Toledo MB, Listopad C, Gosling WD, Williams C, de Oliveira PE, Krisel C (2007b) Holocene fire and occupation in Amazonia: Records from two lake districts. Philos Trans R Soc B 362:209–218.

Bushfire Cooperative Research Centre (2006) Climate change and its impacts on the management of bushfire. Fire Note 4,http://www.bushfirecrc.com/publications/downloads/Firenote_climate190906.pdf Firenote_climate190906.pdf.

Campbell J, Donato D, Azuma D, Law B (2007) Pyrogenic carbon emission from a large wildfire in Oregon, United States. J Geophys Res 112. doi: 10.1029/2007JG000451.

Carcaillet C, Ali AA, Blarquez O, Genries A, Mourier B, Bremond L (2009) Spatial variability of fire history in subalpine forests: From natural to cultural regimes. Ecoscience 16:1–12.

Carcaillet C, Almquist H, Asnong H, Bradshaw RHW, Carrión JS, Gaillard MJ, Gajewski K, Haas JN, Haberle SG, Hadorn P, Müller SD, Richard PJH, Richoz I, Rösch M, Sánchez Goñi MF, Von Stedingk H, Stevenson AC, Talon B, Tardy C, Tinner W, Tryterud E, Wick L, Willis KJ (2002) Holocene biomass burning and global dynamics of the carbon cycle. Chemosphere 49:845–863.

Cardoso MF, Hurtt GC, Moore B, Nobre CA, Prins EM (2003) Projecting future fire activity in Amazonia. Glob Chang Biol 9:656 – 669.

Carmona-Moreno C, Belward A, Malingreau J-P, Hartley A, Garcia-Alegre M, Antonovskiy M, Buchshtaber V, Pivovarov V (2005) Characterizing interannual variations in global fire calendar using data from Earth observing satellites. Glob Chang Biol 11:1537.

Cary G (2002) Importance of a changing climate for fire regimes in Australia. In R Bradstock, J Williams, AM Gill (Eds), Flammable Australia: The Fire Regimes and Biodiversity of a Continent (pp. 26–46). Cambridge: Cambridge University Press.

Castello JD, Leopold DJ, Smallidge PJ (1995) Pathogens, patterns, and processes in forest ecosystems. BioScience 45:16–24.

Charles RW, Michael M (2009) Wildland fire mitigation networks in the western United States. Disasters 33:721–746.

Chuvieco E, Giglio L, Justice C (2008) Global characterization of fire activity: Toward defining fire regimes from Earth observation data. Glob Chang Biol 14:1488–1502.

Clark JS (1990) Fire and climate change during the last 750 yr in northwestern Minnesota. Ecol Monogr 60:135–159.

Cochrane M (2003) Fire science for rainforests. Nature 421:913–919.

Cochrane MA, Alencar A, Schulze MD, Souza CM Jr, Nepstad DC, Lefebvre P, Davidson EA (1999) Positive feedbacks in the fire dynamic of closed canopy tropical forests. Science 284:1832–1835.

Cochrane MA, Barber CP (2009) Climate change, human land use and future fires in the Amazon. Glob Chang Biol 15:601–612.

Cofer W, Winstead E, Stocks B, Goldammer J, Cahoon DR (1998) Crown fire emissions of CO_2, CO, H_2, CH_4 and TNNMHC from a dense jack pine boreal forest fire. Geophys Res Lett 25:3919–3922.

Collinson ME, Steart DC, Scott AC, Glasspool IJ, Hooker JJ (2007) Episodic fire, runoff and deposition at the Palaeocene-Eocene boundary. J Geol Soc 164:87–97.

Conedera M, Tinner W, Neff C, Meurer M, Dickens AF, Krebs P (2009) Reconstructing past fire regimes: Methods, applications, and relevance to fire management and conservation. Quat Sci Rev 28:555–576.

Cook GD, Meyer CP (2009) Culture, ecology, and economy of fire management in North Australian savannas: Rekindling the Wurrk tradition. In J Russell-Smith, P Whitehead, P Cooke (Eds), Fire, Fuels and Greenhouse Gases (p. 416). Melbourne, VIC: CSIRO Publishing.

Cramer W, Kicklighter DW, Bondeau A, Moore III B, Churkina G, Nemry B, Ruimy A, Schloss A and the participants of the Potsdam NPP Model Intercomparison (1999) Comparing global models of terrestrial net primary productivity (NPP): Overview and key results. Glob Chang Biol 5(Suppl. 1):1–15.

Crevoisier C, Shevliakova E, Gloor M, Wirth C, Pacala S (2007) Drivers of fire in the boreal forests: Data constrained design of a prognostic model of burned area for use in dynamic global vegetation models. Geophys Res Lett 112. doi: 10.1029/2006JD008372.

Crutzen PJ, Andreae MO (1990) Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles. Science 250:1669–1678.

D'Antonio CM, Vitousek PM (1992) Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annu Rev Ecol Syst 23:63–87.

Dale L (2009) The True Cost of Wildfire in the Western U.S. (p. 16). Lakewood, CO: Western Forestry Leadership Coalition.

Daniau A-L, Harrison SP, Bartlein PJ (in press) Fire regimes during the last glacial. Quat Sci Rev.

Daniau A-L, Tinner W, Bartlein PJ, Harrison SP, Prentice IC, Brewer S, Friedlingstein P, Harrison-Prentice TI, Inoue J, Marlon JR, et al. (submitted) Hemispherically-asynchronous changes in fire consistent with deglacial climate changes. Nat Geosci.

DeFries RS, Morton DC, Werf GRVd, Giglio L, Randerson JT, Collatz GJ, Houghton RA, Kasibhatla PS, Shimabukuro Y (2008) Fire-related carbon emissions from land use transitions in Southern Amazonia. Geophys Res Lett 35. doi: 10.1029/2008GL035689.

Dentener F, Kinne S, Bond T, Boucher O, Cofala J, Generoso S, Ginoux P, Gong S, Hoelzemann JJ, Ito A, Marelli L, Penner JE, Putaud JP, Textor C, Schulz M, van der Werf GR, Wilson J (2006) Emissions of primary aerosol and precursor gases in the years 2000 and 1750 prescribed data-sets for AeroCom. Atmospheric Chemistry and Physics 6:4321–4344.

Dodson JR, Robinson M, Tardy CT (2005) Two fine-resolution Pliocene charcoal records and their bearing on pre-human fire frequency in south-western Australia. Austral Ecol 30:592–599.

Dombeck MP, Williams JE, Wood CA (2004) Wildfire policy and public lands: Integrating scientific understanding with social concerns across landscapes. Conserv Biol 18: 883–889.

Donovan GH, Brown TC (2007) Be careful what you wish for: The legacy of Smokey Bear. Front Ecol Environ 5:73–79.

Drobyshev I, Goebel PC, Hix DM, Corace RG, Semko-Duncan ME (2008) Pre- and post-European settlement fire history of red pine dominated forest ecosystems of Seney National Wildlife Refuge, Upper Michigan. Can J For Res 38:2497–2514.

Dwyer E, Gregoire J-M, Pereira JMC (2000) Climate and vegetation as driving factors in global fire activity. In JB Innes, MB Beniston, MM Verstraete (Eds), Biomass Burning and Its Inter-Relationships with the Climate System (pp. 171–191). Advances in Global Change Research. New York, NY: Springer.

EEPSEA and WWF (1998) The Indonesian fires and haze of 1997: The economic toll. EEPSEA Research Report rr1998051. Singapore: Economic and Environment Program for Southeast Asia (EEPSEA)/World Wide Fund for Nature (WWF).

Ellicott E, Vermote E, Giglio L, Roberts G (2009) Estimating biomass consumed from fire using MODIS FRE. Geophys Res Lett 36. doi: 10.1029/2009GL038581.

EPICA Community Members (2006) One-to-one coupling of glacial climate variability in Greenland and Antarctica. Nature 444:195–198.

FAO (2007) Fire Management: Global Assessment 2006, FAO Forestry Paper 0258–6150 (p. 151). Food and Agriculture Organization of the United Nations.

Fellows AW, Goulden ML (2008) Has fire suppression increased the amount of carbon stored in western U.S. forests? Geophys Res Lett 35. doi: 10.1029/2008GL033965.

Fernandez P, Botelho H (2003) A review of prescribed burning effectiveness in fire hazard reduction. Int J Wildland Fire 12:117–128.

Ferretti DF, Miller JB, White JWC, Etheridge DM, Lassey KR, Lowe DC, Meure CMM, Dreier MF, Trudinger CM, van Ommen TD, Langenfelds RL (2005) Unexpected changes to the global methane budget over the past 2000 years. Science 309:1714–1717.

Field CB, Raupach MR (2004) The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World (526 pp). Washington, DC: Island Press.

Field RD, Van der Werf G, Shen SSP (2009) Human amplification of drought-induced biomass burning in Indonesia since 1960. Nat Geosci 2:185–188.

Fischer H, Behrens M, Bock M, Richter U, Schmitt J, Loulergue L, Chappellaz J, Spahni R, Blunier T, Leuenberger M, Stocker TF (2008) Changing boreal methane sources and constant biomass burning during the last termination. Nature 452. doi: 10.1038/nature06825.

Fisher JL, Loneragan WA, Dixon K, Delaney J, Veneklaas EJ (2009) Altered vegetation structure and composition linked to fire frequency and plant invasion in a biodiverse woodland. Biol Conserv 142:2270–2281.

Flanner MG, Zender CS, Randerson JT, Rasch PJ (2007) Present-day forcing and response from black carbon in snow. J Geophys Res 112. doi: 10.1029/2006JD008003.

Flannigan M, Campbell I, Wotton M, Carcaillet C, Richard PJH, Bergeron Y (2001) Future fire in Canada's boreal forest: Paleoecology results and general circulation model – regional climate model simulations. Can J For Res 31:854–864.

Flannigan MD, Logan KA, Amiro BD, Skinner WR, Stocks BJ (2005) Future area burned in Canada. Clim Change 72:1–16.

Flannigan MD, Krawchuk MA, de Groot WJ, Wotton BM, Gowman LM (2009) Implications of changing climate for global wildland fire. Int J Wildland Fire 18:483–507.

Frolking S, Palace MW, Clark DB, Chambers JQ, Shugart HH, Hurtt GC (2009) Forest disturbance and recovery: A general review in the context of space-borne remote sensing of impacts on aboveground biomass and canopy structure. J Geophys Res 114:1–27.

Fuentes ER, Segura AM, Holmgren H (1994) Are the responses of matorral shrubs different from those in an ecosystem with a reputed fire history? In JM Moreno, WC Oechel (Eds), The Role of Fire in Mediterranean-Type Ecosystems (pp. 16–25). New York, NY: Springer.

Fulé PZ, Crouse JE, Heinlein TA, Moore MM, Covington WW, Verkamp G (2003) Mixed-severity fire regime in a high-elevation forest: Grand Canyon, Arizona. Landsc Ecol 18:465–486.

Galanter M, Levy II H, Carmichael G (2000) Impacts of biomass burning on tropospheric CO, NO_x, and O_3. J Geophys Res Atmos 105:6633–6653.
Gavin DG, Hu FS, Lertzman K, Corbett P (2006) Weak climatic control of stand-scale fire history during the late Holocene. Ecology 87:1722–1732.
Giglio L, Randerson JT, van der Werf GR, Collatz GJ, Kasibhatla P (2006) Global estimation of burned area using MODIS active fire observations. Atmos Chem Phys Discuss 5:11091–11141.
Gill AM (1977) Management of fire-prone vegetation for plant species conservation in Australia. Search 8:20–26.
Gill AM, Woinarski JCZ, York A (1999). Australia's Biodiversity – Responses to Fire – Plants, Birds and Invertebrates. Biodiversity Technical Paper, Commonwealth of Australia.
Gill MA (2005) Landscape fires as social disasters: An overview of 'the bushfire problem'. Environ Hazards 6:65–80.
Gillett NP, Weaver AJ, Zwiers FW, Flannigan MD (2004) Detecting the effect of climate change on Canadian forest fires. Geophys Res Lett 31. doi: 10.1029/2004GL020876.
Girardin MP (2007) Interannual to decadal changes in area burned in Canada from 1781 to 1982 and the relationship to Northern Hemisphere land temperatures. Glob Ecol Biogeogr 16:557–566.
Girardin MP, Mudelsee M (2008) Past and future changes in Canadian boreal wildfire activity. Ecol Appl 18:391–406.
Glasspool IJ, Edwards D, Axe L (2004) Charcoal in the Silurian as evidence for the earliest wildfire. Geology 32:381–383.
Glover D (2001) The Indonesian fires and haze of 1997: The economic toll. In P Eaton, M Radojevic (Eds), Forest Fires and Regional Haze in Southeast Asia (pp. 227–236). New York, NY: Nova Science Publishers.
Grace JB (2006) Structural Equation Modeling and Natural Systems (365 pp). Cambridge: Cambridge University Press.
Granström A (2001) Fire management for biodiversity in the European boreal forest. Scand J For Res 16(Suppl. 3):62–69.
Grimm EC (1984) Fire and other factors controlling the Big Woods vegetation of Minnesota in the mid-nineteenth century. Ecological Monographs 54:291–311.
Grissino-Mayer HD, Romme WH, Floyd ML, Hanna DD (2004) Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. Ecology 85:1708–1724.
Groisman PY, Sherstyukov BG, Razuvaev VN, Knight RW, Enloe JG, Stroumentova NS, Whitfield PH, Forland E, Hannsen-Bauer I, Tuomenvirta H, Aleksandersson H, Mescherskaya AV, Karl TR (2007) Potential forest fire danger over Northern Eurasia: Changes during the 20th century. Glob Planet Change 56:371–386.
Guyon P, Frank G, Welling M, Chand D, Artaxo P, Rizzo L, Nishioka G, Kolle O, Fritsch H, Dias MAFS, Gatti LV, Cordova M, Andreae MO (2005) Airborne measurements of trace gas and aerosol particle emissions from biomass burning in Amazonia. Atmos Chem Phys Discuss 5: 2791–2831.
Habeck J (1994) Using general land office records to assess forest succession in Ponderosa Pine/Douglas-fir forests in western Montana. Northwest Sci 68:69–78.
Haberle SG, Ledru MP (2001) Correlations among charcoal records of fires from the past 16,000 years in Indonesia, Papua New Guinea, and Central and South America. Quat Res 55:97–104.
Hallett DJ, Mathewes RW, Walker RC (2003) A 1000-year record of forest fire, drought and lake-level change in southeastern British Columbia, Canada. Holocene 13: 751–761.
Hansen J, Nazarenko L (2004) Soot climate forcing via snow and ice albedos. Proc Natl Acad Sci USA 101:423–428.
Hao W, Ward D (1993) Methane production from global biomass burning. J Geophys Res 98:20657–20661.
Hastings MG, Jarvis JC, Steig EJ (2009) Anthropogenic impacts on nitrogen isotopes of ice-core nitrate. Science 324. DOI: 10.1126/science.1170510.
Heinselman ML (1973) Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quat Res 3:329–382.
Heyerdahl EK, Brubaker LB, Agee JK (2001) Spatial controls of historical fire regimes: A multiscale example from the Interior West, USA. Ecol Soc 82:660–678.
Hope G, Kershaw AP, van der Kaars S, Xiangjun S, Liew PM, Heusser LE, Takahara H, McGlone M, Miyoshi N, Moss PT (2004) History of vegetation and habitat change in the Austral-Asian region. Quat Int 118–119:103–126.
Houghton RA, Hall F, Goetz SJ (2009) Importance of biomass in the global carbon cycle. J Geophys Res Biogeosci 114. doi: 10.1029/2009JG000935.
Houweling S, van der Werf G, Klein Goldewijk K, Röckmann T, Aben I (2008) Early anthropogenic emissions and the variation of CH_4 and $^{13}CH_4$ over the last millennium. Glob Biogeochem Cycles 22. doi: 10.1029/2007GB002961.
Hurteau MD, Koch GW, Hungate BA (2008) Carbon protection and fire risk reduction: Toward a full accounting of forest carbon offsets. Front Ecol Environ 6:493–498.
Hutto RL (2008) The ecological importance of severe wildfires: Some like it hot. Ecol Appl 18:1827–1834.
Ickoku C, Giglio L, Wooster MJ, Remner LA (2008) Global characterization of biomass-burning patterns using satellite measurements of fire radiative energy. Remote Sensing Environ 112:2950–2962.
Ito A, Penner JE (2005) Historical emissions of carbonaceous aerosols from biomass and fossil fuel burning for the period 1870–2000. Glob Biogeochem Cycles 19. doi: 10.1029/2004GB002374.
Ito A, Ito A, Akimoto H (2007) Seasonal and interannual variations in CO and BC emissions from open biomass burning in Southern Africa during 1998–2005. Glob Biogeochem Cycles 21:1–13.
Jaegle L, Steinberger L, Martin RV, Chance K (2005) Global partitioning of NO_x sources using satellite observations: Relative roles of fossil fuel combustion, biomass burning and soil emissions. Faraday Discuss 130:407–423.
Jayachandran S (2005). Air quality and infant mortality during Indonesia's massive wildfires in 1997. Bureau for Research in Economic Analysis of Development, Working Paper No. 95.
Jones TP, Chaloner WG (1991) Fossil charcoal, its recognition and paleoatmospheric significance. Palaeogeogr Palaeoclimatol Palaeoecol 97:39–50.
JRC-EU (2005) SAFARI 2000 global burned area map, 1-km, Southern Africa, 2000. Data online from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee (http://daac.ornl.gov/S2K/guides/

spot_veg_burned.html). Joint Research Centre, European Commission (www.jrc.ec.europa.eu/). Ispra, Varese, Italy.

Kajii Y, Kato S, Streets DG, Tsai NY, Shvidenko A, Nilsson S, McCallum I, Minko NP, Abushenko N, Altyntsev D, Khodzer TV (2002) Boreal forest fires in Siberia in 1998: Estimation of area burned and emissions of pollutants by advanced very high resolution radiometer satellite data. J Geophys Res 107:ACH 4-1–ACH 4-8.

Kasischke ES, Christensen NL, Stocks BJ (1995) Fire, global warming, and the carbon balance of boreal forests. Ecol Appl 5:437–451.

Kasischke ES, Bruhwiler LP (2002) Emissions of carbon dioxide, carbon monoxide, and methane from boreal forest fires in 1998. J Geophys Res 108:FFR 2-1–FFR 2-14.

Kasischke ES, Rupp TS, Verbyla DL (2006) Fire trends in the Alaskan boreal forest. In FS Chapin (Ed), Alaska's Changing Boreal Forest (p. 368). New York, NY: Oxford University Press.

Keeley JE, Rundel PW (2005) Fire and the Miocene expansion of C-4 grasslands. Ecol Lett 8:683–690.

Kipfmueller K, Baker WL (2000) A fire history of a subalpine forest in south-eastern Wyoming, USA. J Biogeogr 27:71–85.

Kitzberger T, Swetnam TW, Veblen TT (2001) Inter-hemispheric synchrony of forest fires and the El Niño-Southern Oscillation. Glob Ecol Biogeogr 10:315–326.

Klein Goldewijk K, van Drecht G (2006) HYDE3: Current and historical population and land cover. In AF Bouwman, T Kram, K Klein Goldewijk (Eds), Integrated Modelling of Global Environmental Change. An Overview of IMAGE 2.4. Bilthoven, The Netherlands: Netherlands Environmental Assessment Agency.

Koch D, Hansen J (2005) Distant origins of Arctic black carbon: A goddard institute for space studies modelE experiment. J Geophys Res 110. doi: 10.1029/2004JD005296.

Krawchuk M, Moritz M, Parisien M-A, Van Dorn J, Hayhoe K (2009) Global pyrogeography: The current and future distribution of wildfire. PLoS ONE 4:e5102.

Krawchuk MA, Cumming SG, Flannigan MD, Wein RW (2008) Biotic and abiotic regulation of lightning fire initiation in the mixed wood boreal forest. Ecology 87:458–468.

Krawchuk MA, Moritz MA (2009) Fire regimes of China: Inference from statistical comparison with the United States. Glob Ecol Biogeogr 18:626–639.

Krinner G, Viovy N, Noblet-Ducoudré Nd, Ogé J, Polcher J, Friedlingstein P, Ciais P, Sitch S, Prentice IC (2005) A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system. Glob Biogeochem Cycles 19. doi: 10.1029/2003GB002199.

Kucharik CJ, Foley JA, Delire C, Fisher VA, Coe MT, Lenters JD, Young-Molling C, Ramankutty N (2000) Testing the performance of a dynamic global ecosystem model: Water balance, carbon balance, and vegetation structure. Glob Biogeochem Cycles 14:795–825.

Kurz WA, Stinson G, Rampley GJ, Dymond CC, Neilson ET (2008) Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. Proc Natl Acad Sci USA 105: 1551–1555.

Lafon CW, Grissino-Mayer HD (2007) Spatial patterns of fire occurrence in the central Appalachian Mountains and implications for wildland fire management. Phys Geogr 28: 1–20.

Lavorel S, Flannigan M, Lambin E, Scholes M (2007) Vulnerability of land systems to fire: Interactions among humans, climate, the atmosphere, and ecosystems. Mitig Adapt Strat Glob Change 12:33–53.

Lavoué D, Liousse C, Cachier H, Stocks BJ, Goldammer JG (2000) Modeling of carbonaceous particles emitted by boreal and temperate wildfires at northern latitudes. J Geophys Res 105:26871–26890.

Lehmann CER, Prior LD, Williams RJ, Bowman DMJS (2008) Spatio-temporal trends in tree cover of a tropical mesic savanna are driven by landscape disturbance. J Appl Ecol 45:1304–1311.

Lenihan J, Bachelet D, Neilson R, Drapek R (2008) Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. Clim Change 87:215–230.

Lenihan JM, Daly C, Bachelet D, Neilson RP (1998) Simulating broad-scale fire severity in a dynamic global vegetation model. Northwest Sci 72:91–103.

Lenton TM (2001) The role of land plants, phosphorus weathering and fire in the rise and regulation of atmospheric oxygen. Global Chang Biol 7:613–629.

Litvak ME, Miller S, Wofsy SC, Goulden M (2003) Effect of stand age on whole ecosystem CO_2 exchange. J Geophys Res 108. doi: 10.1029/2001JD000854.

Liu H, Randerson JT, Lindfors J, Chapin III FS (2005) Changes in the surface energy budget after fire in boreal ecosystems of interior Alaska: An annual perspective. J Geophys Res 110. doi: 10.1029/2004JD005158.

Lohman DJ, Bickford D, Sodhi NS (2007) The burning issue. Science 316:376.

Lynch DL (2004) What do forest fires really cost? J For 102:42–49.

Marlon J, Bartlein P, Carcaillet C, Gavin DG, Harrison SP, Higuera PE, Joos F, Power MJ, Prentice CI (2008) Climate and human influences on global biomass burning over the past two millennia. Nat Geosci 1:697–701.

Marlon J, Bartlein P, Walsh MK, Harrison SP, Brown KJ, Edwards ME, Higuera PE, Power MJ, Anderson RS, Briles CE, et al. (2009) Wildfire responses to abrupt climate change in North America. Proc Natl Acad Sci 106:2519–2524.

Marynowski L, Simoneit BRT (2009) Widespread Upper Triassic to Lower Jurassic wildfire records from Poland: Evidence from charcoal and pyrolytic polycyclic aromatic hydrocarbons. Palaios 24:784–798.

Mazhitova GG (2000) Pyrogenic dynamics of permafrost-affected soils in the Kolyma upland. Eurasian Soil Sci 33:542–551.

McGlone MS, Wilmshurst JM (1999) Holocene record of climate, vegetation change and peat bog development, east Otago, New Zealand.

McWethy D, Whitlock C, Wilmshurst JM, McGlone MS, Li X (2009) Rapid deforestation of South Island, New Zealand by early Polynesian fires. Holocene 19:883–897.

Menon S, Hansen J, Nazarenko L, Luo Y (2002) Climate effects of black carbon aerosols in China and India. Science 297:2250–2253.

Miller GH, Magee JW, Johnson BJ, Fogel ML, Spooner NA, McCulloch MT, Ayliffe LK (1999) Pleistocene

extinction of Genyornis newtoni: Human impact on Australian megafauna. Science 283:205–208.
Mitchell SR, Harmon ME, O'Connell KEB (2009) Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecol Appl 19:643–655.
Moritz MA, Stephens SL (2008) Fire and sustainability: Considerations for California's altered future climate. Clim Change 87:S265–S271.
Morton DC, DeFries RS, Randerson JT, Giglio L, Schroeder W, Werf GRvd (2008) Agricultural intensification increases deforestation fire activity in Amazonia. Glob Chang Biol 14:2262–2275.
Mota BW, Pereira JMC, Oom D, Vasconcelos MJP, Schultz M (2006) Screening the ESA ATSR-2 World Fire Atlas (1997–2002). Atmos Chem Phys 6:1409–1424.
Mouillot F, Field CB (2005) Fire history and the global carbon budget: A 1° × 1° fire history reconstruction for the 20th century. Glob Chang Biol 11:398–420.
Mutch RW (1970) Wildland fires and ecosystems – A hypothesis. Ecology 51:1046–1051.
Myneni RB, Dong J, Tucker CJ, Kaufmann RK, Kauppi PE, Liski J, Zhou L, Alexeyev V, Hughes MK (2001) A large carbon sink in the woody biomass of northern forests. Proc Natl Acad Sci USA 98:14784–14789.
Naik V, Mauzerall DL, Horowitz LW, Schwarzkopf MD, Ramaswamy V, Oppenheimer M (2007) On the sensitivity of radiative forcing from biomass burning aerosols and ozone to emission location. Geophys Res Lett 34:1–5.
Narayan C, Fernandes P, van Brusselen J, Schuck A (2007) Potential for CO_2 emissions mitigation in Europe through prescribed burning in the context of the Kyoto Protocol. For Ecol Manage 251:164–173.
Nepstad D, Lefebvre P, Da Silva UL, Tomasella J, Schlesinger P, Solórzano L, Moutinho P, Ray D, Benito JG (2004) Amazon drought and its implications for forest flammability and tree growth: A basin-wide analysis. Glob Chang Biol 704–717.
New M, Lister D, Hulme M, Makin I (2002) A high-resolution data set of surface climate over global land areas. Clim Res 21:1–25.
Ohlson M, Tryterud E (2000) Interpretation of the charcoal record in forest soils: Forest fires and their production and deposition of macroscopic charcoal. Holocene 10: 519–525.
Page SE, Siegert F, Rieley JO, Boehm H-DV, Jaya A, Limin S (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature 420:61–65.
Parisien M-A, Moritz MA (2009) Environmental controls on the distribution of wildfire at multiple spatial scales. Ecol Monogr 79:127–154.
Paula, S, Arianoutsou, M, Kazanis, D, Tavsanoglu, C, Lloret, F, Buhk, C, Ojeda, F, Luna, B, Moreno, JM, Rodrigo, A, Espelta, JM, Palacio, S, Fernández-Santos, B, Fernandes, PM (2009) Fire-related traits for plant species of the Mediterranean basin. Ecology 90:1420–1420.
Pausas JG, Bradstock RA, Keith DA, Keeley JE (2004) Plant functional traits in relation to fire in crown-fire ecosystems. Ecology 85:1085–1100.
Pausas JG, Keeley JE (2009) A burning story: The role of fire in the history of life. BioScience 59:593–601.
Pechony O, Shindell DT (2009) Fire parameterization on a global scale. J Geophys Res 114:1–10.
Pfister G, Hess PG, Emmons LK, Lamarque J-F, Wiedinmyer C, Edwards DP, Pétron G, Gille JC, Sachese GW (2005) Quantifying CO emissions from the 2004 Alaskan wildfires using MOPITT CO data. Geophys Res Lett 32. doi: 10.1029/2005GL022995.
Piñol J, Terradas J, Lloret F (1998) Climate warming, wildfire hazard, and wildfire occurrence in coastal eastern Spain. Clim Change 38:345–357.
Pitman AJ, Hesse P (2007) The significance of large scale land cover change on the Australian palaeomonsoon. Quat Sci Rev 26:189–200.
Power MJ, Whitlock C, Bartlein PJ, Stevens LR (2006) Fire and vegetation history during the last 3800 years in northwestern Montana. Geomorphology 75:420–436.
Power MJ, Marlon J, Ortiz N, Bartlein PJ, Harrison SP, Mayle FE, Ballouche A, Bradshaw RHW, Carcaillet C, Cordova C, et al. (2008) Changes in fire regimes since the Last Glacial Maximum: An assessment based on a global synthesis and analysis of charcoal data. Clim Dyn 30:887–907.
Power MJ, Marlon JR, Bartlein PJ, Harrison SP (2010) Fire history and the Global Charcoal Database: A new tool for hypothesis testing and data exploration. Palaeogeogr Palaeoclimatol Palaeoecol 291:52–59.
Pyne SJ (1995) World Fire: The Culture of Fire on Earth (384 pp). Seattle, WA: University of Washington Press.
Pyne SJ, Andrews PL, Laven RD (1996) Introduction to Wildland Fire (769 pp). New York, NY: Wiley.
Ramanathan V, Carmichael G (2008) Global and regional climate changes due to black carbon. Nat Geosci 1:221–227.
Randerson JR, Thompson MV, Conway TJ, Fung I, Field CB (1997) The contribution of terrestrial sources and sinks to trends in the seasonal cycle of atmospheric carbon dioxide. Glob Biogeochem Cycles 11:535–560.
Randerson JT, Liu H, Flanner MG, Chambers SD, Jin Y, Hess PG, Pfister G, Mack MC, Treseder KK, Welp LR, Chapin FS, Harden JW, Goulden ML, Lyons E, Neff JC, Schuur EAG, Zender CS (2006) The impact of boreal forest fire on climate warming. Science 314:1130–1132.
Randerson JT, Van der Werf GR, Giglio L, Collatz GJ, Kasibhatla PS (2007). Global Fire Emissions Database, Version 2 (GFEDv2.1). Available on-line [http://daac.ornl.gov/] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. doi: 10.3334/ORNLDAAC/849.
Rasker R (2009) Cost of fighting fires on public lands (p. 4). Bozeman, MT: Headwaters Economics.
Riaño D, Ruiz J, Isidoro D, Ustin S (2007) Global spatial patterns and temporal trends of burned area between 1981 and 2000 using NOAA-NASA Pathfinder. Glob Chang Biol 13:40–50.
Rinsland CP, Luo M, Logan JA, Beer R, Worden HM, Worden JR, Bowman K, Kulawik SS, Rider D, Osterman G, Gunson M, Goldman A, Shephard M, Clough SA, Rodgers C, Lampel M, Chiou L (2006) Measurements of carbon monoxide (CO) distributions by the tropospheric emission spectrometer instrument onboard the Aura spacecraft: Overview of analysis approach and examples of initial results. Geophys Res Lett 33. doi: 10.1029/2006GL027000.

Roy DP, Boschetti L, Justice CO, Ju J (2008) The Collection 5 MODIS Burned Area Product – Global Evaluation by Comparison with the MODIS Active Fire Product. Remote Sensing Environ 112:3690–3707.
Running SW (2006) Is global warming causing more, larger wildfires? Science 313:927–928.
Russell-Smith J, Yates C, Whitehead P, Smith R, Craig R, Allan G, Thackway R, Frakes I, Cridland S, Meyer M (2007) Bushfires 'down under': Patterns and implications of contemporary Australian landscape burning. Int J Wildland Fire 16:361–377.
Schafer JS, Eck TF, Holben BN, Artaxo P, Yamasoe MA, Procopio AS (2002) Observed reductions of total solar irradiance by biomass-burning aerosols in the Brazilian Amazon and Zambian Savanna. Geophys Res Lett 29. doi: 10.1029/2001GL014309.
Scholes RJ, Archer SR (1997) Tree-grass interactions in savannas. Annu Rev Ecol Syst 28:517–544.
Scholze M, Knorr W, Arnell NW, Prentice IC (2006) A climate-change risk analysis for world ecosystems. Proc Natl Acad Sci USA 103:13116–13120.
Schultz MG, Heil A, Hoelzemann JJ, Spessa A, Thonicke K, Goldammer JG, Held AC, Pereira JMC, van het Bolscher M (2008) Global wildland fire emissions from 1960 to 2000. Glob Biogeochem Cycles 22:1–17.
Schwilk DW, Ackerly DD (2001) Flammability and serotiny as strategies: Correlated evolution in pines. Oikos 94: 326–336.
Schwilk DW, Kerr B (2002) Genetic niche hiking: An alternative explanation for the evolution of flammability. Oikos 99:431–442.
Scott AC (2000) The Pre-Quaternary history of fire. Palaeogeogr Palaeoclimatol Palaeoecol 164:281–329.
Scott AC, Glasspool IJ (2006) The diversification of Paleozoic fire systems and fluctuations in atmospheric oxygen concentration. Proc Natl Acad Sci USA 103: 10861–10865.
Sherwood S (2002) A microphysical connection among biomass burning, cumulus clouds, and stratospheric moisture. Science 295:1272–1275.
Shindell D, Faluvegi G (2009) Climate response to regional radiative forcing during the twentieth century. Nat Geosci 2:294–300.
Shlisky A, Waugh J, Gonzalez P, Gonzalez M, Manta M, Santoso H, Alvarado E, Nuruddin AA, Rodríguez-Trejo DA, Swaty R, Schmidt D, Kaufmann M, Myers R, Alencar A, Kearns F, Johnson D, Smith J, Zollner D (2007). Fire, ecosystems and people: Threats and strategies for global biodiversity conservation. In The Nature Conservance Global Fire Initiative (p. 17). The Nature Conservancy Global Fire Initiative Technical Report 2007-2, Boulder, CO.
Shuman B, Webb III T, Bartlein PJ, Williams JW (2002) The anatomy of a climatic oscillation: Vegetation change in eastern North America during the Younger Dryas chronozone. Quat Sci Rev 21:1777–1791.
Silva JMN, Pereira JMC, Cabral AI, Sá ACL, Vasconcelos MJP, Mota B, Grégoire J-M (2003) An estimate of the area burned in southern Africa during the 2000 dry season using SPOT-VEGETATION satellite data. J Geophys Res 108. doi: 10.1029/2002JD002320.
Skroch M, Swetnam TW (2008) Public Should Accept More Frequent, but Less Destructive, Forest Fires. Tucson, AZ: Arizona Daily Star.
Smith AMS, Wooster MJ (2005) Remote classification of head and backfire types from MODIS fire radiative power observations. Int J Wildland Fire 14:249–254.
Stephenson N (1998) Actual evapotranspiration and deficit: Biologically meaningful correlates of vegetation distribution across spatial scales. J Biogeogr 25:855–870.
Stevenson J, Hope G (2005) A comparison of late Quaternary forest changes in New Caledonia and northeastern Australia. Quat Res 64:372–383.
Stocks BJM, Mason JA, Todd JB, Bosch EM, Wotton BM, Amiro BD, Flannigan MD, Hirsch KG, Logan KA, Martell DL, Skinner WR (2002) Large forest fires in Canada, 1959–1997. J Geophys Res Atmos. doi: 10.1029/2001JD000484, 2003
Sukhinin AI, French NHF, Kasischke ES, Hewson JH, Soja AJ, Csiszar IA, Hyer EJ, Loboda T, Conrad SG, Romasko VI, Pavlichenko EA, Miskiv SI, Slinkina OA (2004) AVHRR-based mapping of fires in Russia: New products for fire management and carbon cycle studies. Remote Sensing Environ 93:546– 564.
Swetnam TW (1993) Fire history and climate change in giant sequoia groves. Science 262:885–889.
Syphard AD, Radeloff VC, Hawbaker TJ, Stewart SI (2009) Conservation threats due to human-caused increases in fire frequency in Mediterranean-climate ecosystems. Conserv Biol 23:758–769.
Tacconi L (2003). Fires in Indonesia: Causes, Costs and Policy Implications. Occasional Paper No. 38. Jakarta, Indonesia: Center for International Forestry Research.
Tansey K, Grégoire J-M, Defourny P, Leigh R, Pekel J-F, van Bogaert E, Bartholomé E (2008) A new, global, multi-annual (2000–2007) burnt area product at 1 km resolution. Geophys Res Lett 35. doi: 10.1029/2007GL031567.
Thonicke K, Venevsky S, Sitch S, Cramer W (2001) The role of fire disturbance for global vegetation dynamics: Coupling fire into a dynamic global vegetation model. Glob Ecol Biogeogr 10:661–677.
Thonicke K, Prentice IC, Hewitt C (2005) Modeling glacial-interglacial changes in global fire regimes and trace gas emissions. Glob Biogeochem Cycles 19. doi: 10.1029/2004GB002278.
Tilman D, Lehman C (2001) Human-caused environmental change: Impacts on plant diversity and evolution. Proc Natl Acad Sci 98:5433–5440.
Tolonen K (1986) Charred particle analysis. In BE Berglund (Ed), Handbook of Holocene Palaeoecology and Palaeohydrology (pp. 485–490). New York, NY: Wiley.
Tomich TP, Thomas DE, van Noordwijk M (2004) Environmental services and land use change in Southeast Asia: From recognition to regulation or reward? Agric Ecosyst Environ 104:229–244.
USDA (2006) Audit Report: Forest Service Large Fire Suppression Costs (p. 48). United States Department of Agriculture.
van der Werf GR, Randerson JT, Collatz GJ, Giglio L, Kasibhatla PS, Avelino A, Olsen SC, Kasischke ES (2004) Continental-scale partitioning of fire emissions during the 1997–2001 El Nino/La Nina period. Science 303:73–76.

van der Werf GR, Randerson JT, Giglio L, Collatz GJ, Kasibhatla PS (2006) Interannual variability in global biomass burning emission from 1997 to 2004. Atmos Chem Phys 6:3423–3441.

van der Werf GR, Dempewolf J, Trigg SN, Randerson JT, Kasibhatla PS, Giglio L, Murdiyarso D, Peters W, Morton DC, Collatz GJ, Dolman AJ, DeFries RS (2008a) Climate regulation of fire emissions and deforestation in equatorial Asia. Proc Natl Acad Sci USA 105:20350–20355.

van der Werf GR, Randerson JT, Giglio L, Gobron N, Dolman AJ (2008b) Climate controls on the variability of fires in the tropics and subtropics. Glob Biogeochem Cycles 22. doi: 10.1029/2007GB003122, 2008

van Wagtendonk JW (2007) The history and evolution of wildland fire use. Fire Ecol Spec Issue 3:3–17.

Veblen TT, Kitzberger T, Villalba R, Donnegan J (1999) Fire history in northern Patagonia: The roles of humans and climatic variation. Ecol Monogr 69:47–67.

Venevsky S, Thonicke K, Sitch S, Cramer W (2002) Simulating fire regimes in human-dominated ecosystems: Iberian Peninsula case study. Glob Chang Biol 8:984–998.

Walsh MK, Whitlock C, Bartlein PJ (2008) A 14,300-year-long record of fire-vegetation-climate linkages at Battle Ground Lake, southwestern Washington. Quaternary Research 70:251–264.

Westerling AL, Gershunov A, Brown TJ, Cayan DR, Dettinger MD (2003) Climate and wildfire in the western United States. Bull Am Meteor Soc 84:595–604.

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. Science 313:940–943.

Whelan RJ (1995) The Ecology of Fire (346 pp). Cambridge, NY: Cambridge University Press.

Wiedinmyer C, Neff J (2007) Estimates of CO_2 from fires in the United States: Implications for carbon management. Carbon Balance Manag 2. doi: 10.1186/1750–0680–1182–1110.

Williams R, Griffiths A, Allan G (2002) Fire regimes and biodiversity in the wet-dry tropical savanna landscapes of northern Australia. In R Bradstock, J Williams, A Gill (Eds), Flammable Australia: Fire Regimes and Biodiversity of a Continent (pp. 281–304). Cambridge: Cambridge University Press.

Williams R, Hutley L, Cook G, Russell-Smith J, Edwards A, Chen X (2004) Assessing the carbon sequestration potential of mesic savannas in the Northern Territory, Australia: Approaches, uncertainties and potential impacts of fire. Funct Plant Biol 31:415–422.

Williams J, Shuman B, Bartlein P (2008) Rapid responses of the prairie-forest ecotone to early Holocene aridity in mid-continental North America. Glob Planet Change 66:195–207.

Wilson JB, King WM (1995) Human-mediated vegetation switches as processes in landscape ecology. Landsc Ecol 10:191–196.

Winkler H, Formenti P, Esterhuyse D, Swap RJ, Helas G, Annegarn H, Andreae M (2008) Evidence for large-scale transport of biomass burning aerosols from sunphotometry at a remote South African site. Atmos Environ 42: 5569–5578.

Zoltai S (1993) Cyclic development of permafrost in the peatlands of northwestern Alberta, Canada. Arct Alp Res 25:240–246.