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Implications of changing climate for global wildland fire

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Abstract. Wildland fire is a global phenomenon, and a result of interactions between climate–weather, fuels and people. Our climate is changing rapidly primarily through the release of greenhouse gases that may have profound and possibly unexpected impacts on global fire activity. The present paper reviews the current understanding of what the future may bring with respect to wildland fire and discusses future options for research and management. To date, research suggests a general increase in area burned and fire occurrence but there is a lot of spatial variability, with some areas of no change or even decreases in area burned and occurrence. Fire seasons are lengthening for temperate and boreal regions and this trend should continue in a warmer world. Future trends of fire severity and intensity are difficult to determine owing to the complex and non-linear interactions between weather, vegetation and people. Improved fire data are required along with continued global studies that dynamically include weather, vegetation, people, and other disturbances. Lastly, we need more research on the role of policy, practices and human behaviour because most of the global fire activity is directly attributable to people.

Additional keywords: area burned, carbon, emissions, fire activity, forest fire, intensity, management, modelling, occurrence, review, season, severity, weather.

Introduction

Wildland fire is a critical component in the terrestrial and atmospheric dynamics of our earth system. Recent advances in remote sensors on board satellites have made it clear just how prevalent fire is on a global scale (see Figs 1, 2). Historical (1960–2000) estimates of global annual area burned by wildland fires range from 273 to 567 Mha, with an average of 383 Mha (Schultz *et al*. 2008). This range of values is in line with short-term annual area burned estimates of 300–450 Mha (van der Werf *et al*. 2006; Tansey *et al*. 2008) for recent years, although Mouillot and Field (2005) estimated 608 Mha at the end of the 20th century. Approximately 80–86% of the global area burned occurs in grassland and savannas, primarily in Africa and Australia, but also in South Asia and South America, while the remainder occurs in forested regions of the world (Mouillot and Field 2005; van der Werf *et al*. 2006) (Fig. 3). In fact, the distribution and ecological properties of many of the world's biomes are affected to a large degree by their fire regime (Bond *et al*. 2005). From a global perspective, fires are generally absent poleward of 70°N and 70°S, progressively more frequent towards the tropics, and dropping sharply at the equator (Mouillot and Field 2005). Biomass burning is a global-scale and continuous phenomenon with fire occurring all year round in both hemispheres (Fig. 1; Carmona-Moreno *et al*. 2005).

The objective of the present paper is to summarize our understanding of recent historical global fire activity and then examine existing research in order to outline potential responses of global wildland fire to rapid climate change. Many of the examples we use are from North America; this is because 75% of the papers on wildland fire and climate change are from North America (see Table 1). We explore options for future research and management directions and highlight gaps in our data and understanding. In summary, we ask, will rapid changes in weather, vegetation, and the human population initiate a breaking point such that surprising changes in fire activity may cause significant and far-reaching impacts?

Global fire

Long-term global data on fire activity is lacking, but proxies such as charcoal records indicate there has been a global monotonic increase in wildland fire since the last glacial maximum 21 000 years ago, with increased spatial heterogeneity in the last 12 000 years (Power *et al*. 2008). More recently, there is evidence from some regions of a trend towards more fires affecting a larger area, and burning with greater severity during the last few decades (FAO 2007). Mouillot and Field (2005) estimate that the global average area burned decreased from 535 to 500 Mha year^{-1} during the first half of the 20th century. This was largely attributed to human factors such as fire suppression and fire exclusion policies, increased firefighting efficiency, improved fire prevention, abandonment of shifting cultivation in some areas, and permanent agricultural practice in others. However, the global area burned trend reversed during the second half of the last century, and was estimated to have increased to

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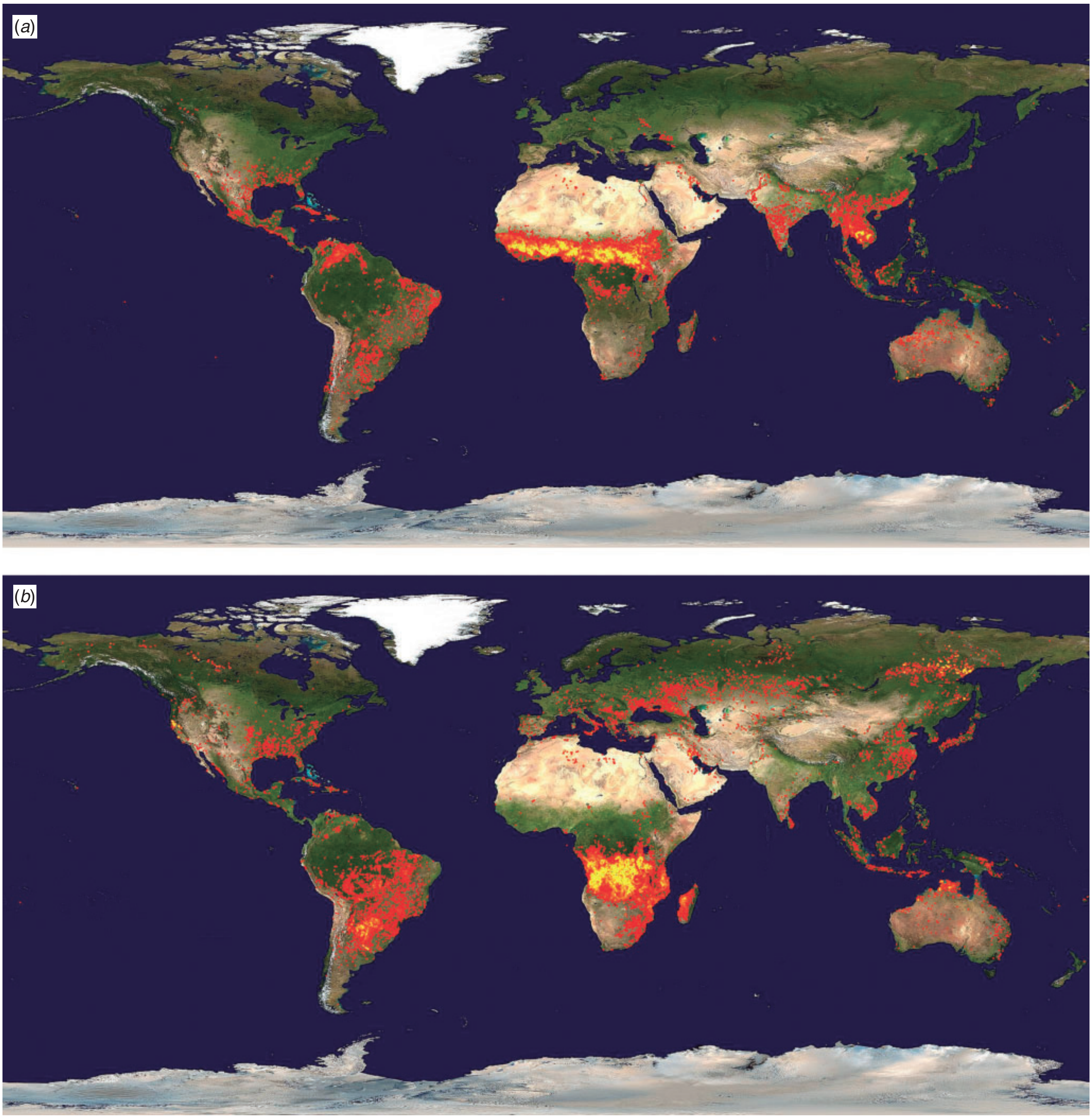

Fig. 1. Examples of recent global fire activity for (*a*) 11–20 January 2008; and (*b*) 9–18 July 2008. Each of these fire maps accumulates the locations of the fires detected by MODIS (Moderate Resolution Imaging Spectroradiometer) on board the Terra and Aqua satellites over a 10-day period. Each colored dot indicates a location where MODIS detected at least one fire during the compositing period. Color ranges from red where the fire count is low to yellow where number of fires is large. Images provided by the MODIS Rapid Response System (http://rapidfire.sci.gsfc.nasa.gov/firemaps/?2008011-2008020; accessed 27 September 2008).

608 Mha year^{-1}. This substantial shift in global area burned is not broad-based across all regions (Marlon *et al*. 2008). In fact, regional fire regimes are showing great difference in the direction and amplitude of their changes. Mouillot and Field (2005) and Marlon *et al*. (2008) attribute much of these differences to anthropogenic effects. Savanna and grassland fires continue to increase, primarily in the tropics, but also in temperate regions.

The biggest change in biomass burning over the last few decades has been an exponential increase of fire in tropical forests. Forest fire size and frequency are increasing across

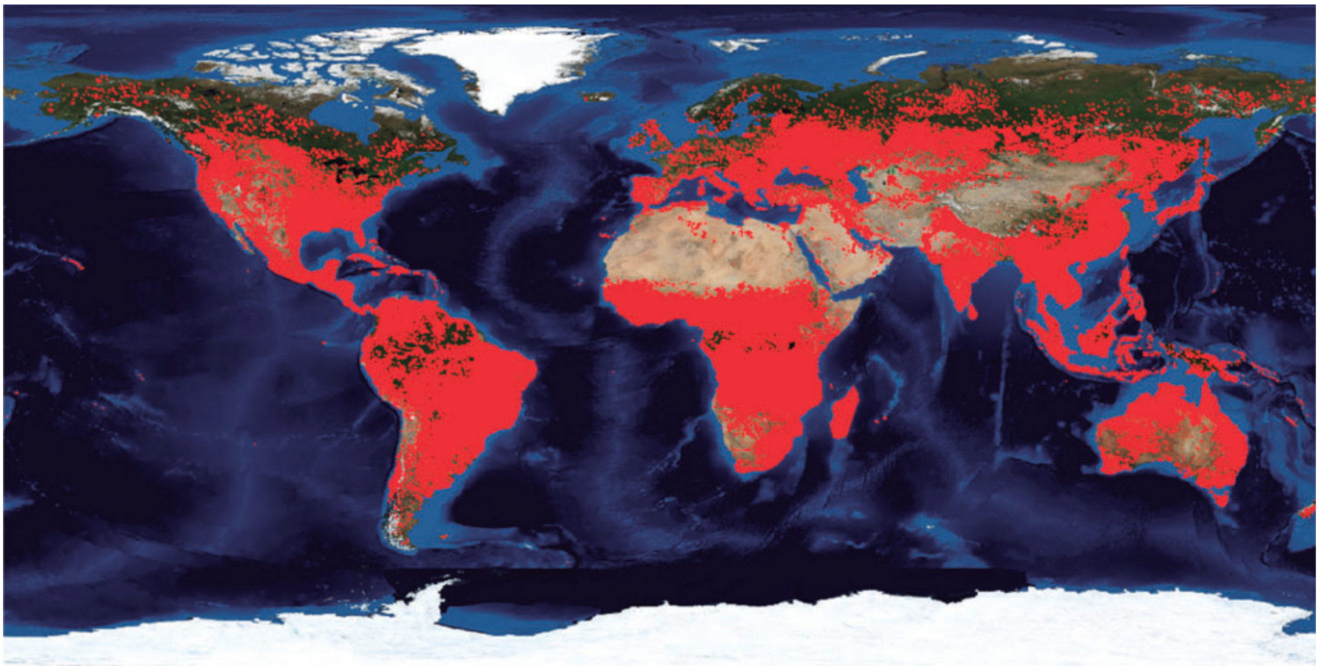

Fig. 2. MODIS active fire detections for 2007. Red points indicate fire locations and global distribution of fire occurrence; image does not represent area burned (red points are much larger than the actual area burned). Images provided by Fire Information for Resource Management Systems, University of Maryland.

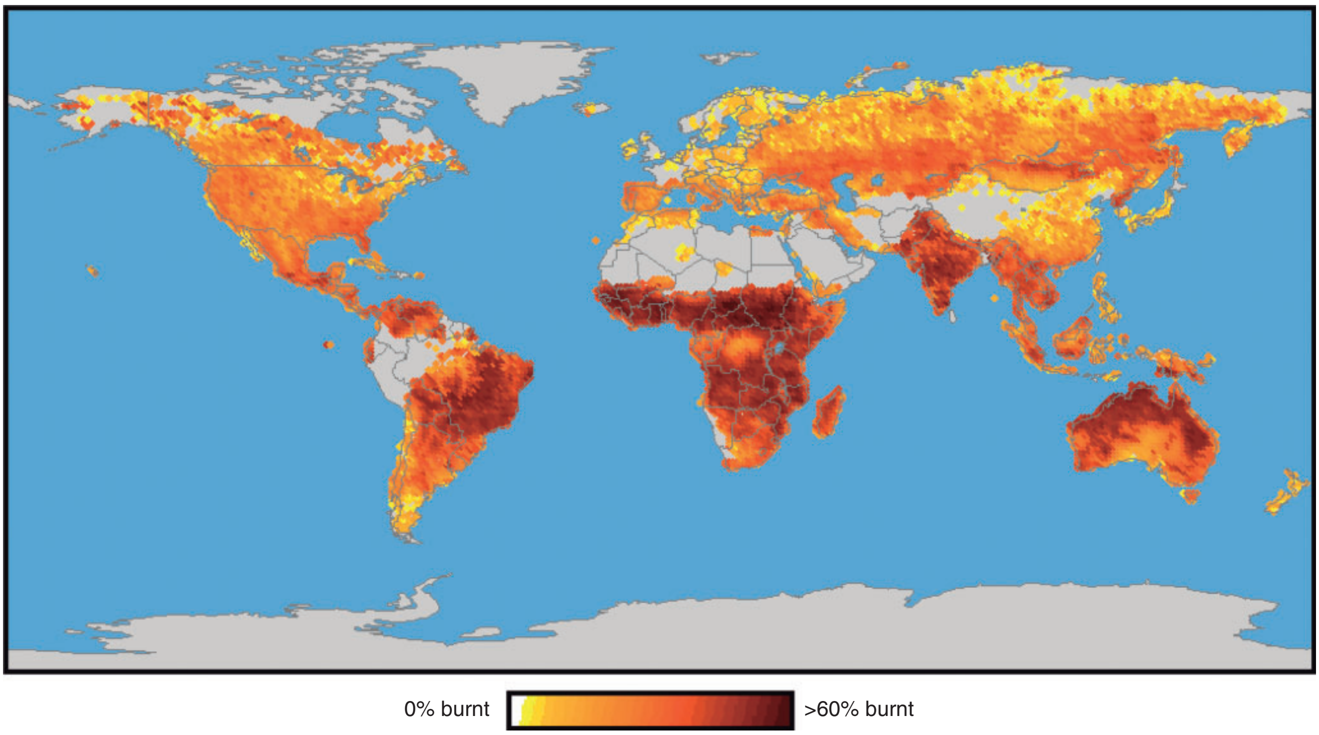

Fig. 3. 1° × 1° global map of average annual area burned (percentage of cell burned) for 1960 to 2000; data from Mouillot and Field (2005).

Table 1. Summary of future fire activity in locations around the world; shows the generalized results of studies including the fire activity metric(s) (fire weather, area burned, fire occurrence, fire season, fire intensity, and fire severity) used, the location of the study area, the projected change in the fire activity and the time period the change is expected, and the general trend (increase, +; decrease, −; or both, ±) exhibited by the predicted fire activity

Fire activity metric	Location	Projected change	Time period or scenario	General trend	Reference
Fire weather, area burned	Canada	~40% increase due to 46% increase in severe fire weather (seasonal severity ratio, SSR).	$2 \times CO_2$	+	Flannigan and Van Wagner 1991
Intensity	USA (California)	Indirect effects of climate through changes in fuel load and forest composition with climate change.	$2 \times CO_2$	+	Malanson and Westman 1991
Seasonality	Canada	Length will increase by an average of 22% (range of 16–39% depending on area), which is equal to 30 days (range of 24–51, depending on area).	$2 \times CO_2$	+	Wotton and Flannigan 1993
Area burned, occurrence	Continental USA	78% increase due to 44% increase in lightning ignitions.	2100	+	Price and Rind 1994
Fire weather, occurrence	Australia	Increase in forest fire danger* index over most of Australia, some areas of decrease.	$2 \times CO_2$	±	Beer and Williams 1995
Fire weather	Canada	South-eastern boreal forest will show a decrease in fire weather index (FWI); western Canada FWI will increase dramatically.	$2 \times CO_2$	±	Bergeron and Flannigan 1995
Fire weather	North America, Northern Europe	FWI will decrease in eastern and western Canada; FWI will increase in central North America; FWI will increase over southern Sweden and south-east Finland; remainder of northern Europe shows decreased FWI values.	$2 \times CO_2$	±	Flannigan *et al*. 1998
Seasonality	USA	Number of months without lightning fires will go from 3 to 1; earlier start to fire season.	$2 \times CO_2$	+	Goldammer and Price 1998
Fire weather, seasonality	Canada and Russia (boreal forest)	Fire season: earlier start. Fire weather: increase in severity (monthly severity ratio (MSR) and SSR); more extreme MSR and SSR expected.	$2 \times CO_2$	+	Stocks *et al*. 1998
Fire weather	North America	SSR will increase by 10–50% over most of North America.	$2 \times CO_2$	+	Flannigan *et al*. 2000

Area burned, occurrence	Canada (west-central Alberta)	Area burned: 62% increase in area burned; 650% increase in number of years with annual burn over 1000 ha. Fire occurrence: 40% decrease in fire return interval; 3% increase in number of fires.	$2 \times CO_2$	+	Li *et al*. 2000
Fire weather	Canada (western)	FWI predicted to increase in most of western Canada by more than 20%, with some areas of no change, and some areas of decreases.	$1 \times CO_2$ *v.* $2 \times CO_2$	±	Amiro *et al*. 2001*b*
Fire weather	Canada (boreal forest)	FWI will decrease for some of eastern Canada, but increase for most of the rest of the country.	$2 \times CO_2$	±	Flannigan *et al*. 2001
Intensity	Canada (boreal forest in Saskatchewan)	Increase in fire intensity at $2 \times CO_2$; little additional change detected under $3 \times CO_2$ conditions.	$2 \times CO_2$; $3 \times CO_2$	+	Kafka *et al*. 2001
Fire weather, occurrence, seasonality	Australia	Fire weather, occurrence: Increase in forest fire danger* index at all sites (eight across the country) due to increased number of days of high, very high, and extreme fire danger. Seasonality: some sites are expected to have an earlier or later peak in the fire season; some sites expected to have longer or shorter fire season.	$2 \times CO_2$	±	Williams *et al*. 2001
Occurrence	Savanna areas of South America, Africa, Australia	Fire frequency predicted to increase owing to vegetation clearing, climate, and feedbacks between the two.	Present *v.* cleared savannah	+	Hoffmann *et al*. 2002
Occurrence	Europe (France)	Decrease in time interval between fires by 3–10 years (depending on climate scenario used and whether it was forest or shrubland).	Reference 1960–97 *v.* 2072	+	Mouillot *et al*. 2002
Area burned	USA	Area burned to increase 4–31% (depending on scenario and model)	1895–1994 *v.* 1995–2100	+	Bachelet *et al*. 2003
Area burned	South America (Amazonia)	Additional area of 9240–246 000 km^2 $year^{-1}$ (range based on two different scenarios of deforestation).	Two scenarios: intermediate and complete deforestation	+	Cardoso *et al*. 2003

(*Continued*)

Table 1 . (Continued)

Fire activity metric	Location	Projected change	Time period or scenario	General trend	Reference
Area burned, occurrence, intensity, severity	Western Canada	Area burned: 14–137% increase (depending on location). Fire occurrence: shorter fire cycle. Fire severity: greater depth of burn, greater total fuel consumption. Fire intensity: greater intensity.	1975–90 *v.* 2080–2100	+	de Groot *et al*. 2003
Occurrence	Canada (Ontario)	Human-caused fires could increase 18% or 50%.	Recent history *v.* 2020–40; end of 21st century	+	Wotton *et al*. 2003
Occurrence	Canada	Burn rate will increase on average; most areas will increase, some will decrease.	2 × CO_2; 3 × CO_2	±	Bergeron *et al*. 2004
Fire weather, occurrence	USA (western)	Increase in the number of days of high fire danger*.	1975–96 *v.* 2089	+	Brown *et al*. 2004
Area burned, occurrence	USA (northern California)	Area burned: increased by 50%. Fire occurrence: fire return intervals were cut in half.	2 × CO_2	+	Fried *et al*. 2004
Area burned	USA (Alaska)	Area burned to increase 14–34% (depending on scenario).	1922–96 *v.* 2025–99	+	Bachelet *et al*. 2005
Area burned	Canada	74–118% increase (range varies with location and model used).	Reference 1959–97 *v.* 2080–99 (3 × CO_2)	+	Flannigan *et al*. 2005
Area burned, occurrence	Canada (Yukon)	Fire occurrence: mean number of fires per year to increase 77%, maximum annual number of fires to increase 68%. Area burned: mean annual area burned to increase 33%, maximum annual area burned to increase 227%.	1960–2000 *v.* 2040–69	+	McCoy and Burn 2005
Area burned, occurrence	Canada (Ontario)	Area burned: 31% or 78% increase. Fire occurrence: 15% or 50% increase.	Reference 2000 *v.* 2040 or 2090	+	Wotton *et al*. 2005
Occurrence	Canada (southern Quebec)	Burn rate for Quebec will increase.	2 × CO_2; 3 × CO_2	+	Bergeron *et al*. 2006
Fire weather, seasonality	Canada (NWT, north-west Canada)	Fire season length: average increase of 30–50 days (depending on model). Fire weather: SSR to increase on average 19–44% (depending on model); large spatial variability with areas of increases and some areas of no change or decreases.	3 × CO_2	±	Kochtubajda *et al*. 2006

Fire weather	USA (California)	Increased fire weather risk due to a shift in seasonality of high-wind fire weather conditions.	Reference 1965–94 *v.* 2005–34, 2035–64, and 2070–99	+	Miller and Schlegel 2006
Fire weather, seasonality	Europe (Mediterranean)	Fire season: increased length. Fire weather: increased number of years with high fire risk; increase of extreme fire weather events.	2100	+	Moriondo *et al*. 2006
Occurrence	Global	Fire frequency will increase in some areas and decrease in others (highly variable – see paper); changes are more extreme with greater increase in temperature.	1961–90 *v.* 2071–2100	±	Scholze *et al*. 2006
Occurrence	Switzerland	Increase in fire occurrence from essentially zero to a level that may be an important factor in shaping the landscape.	1961–2000 *v.* 2071–2100	+	Schumacher and Bugmann 2006
Area burned, occurrence	Germany (Brandenburg)	Area burned and number of fires are expected to decrease, but depending on scenario there may be slight increases.	2001 *v.* 2100	–	Thonicke and Cramer 2006
Fire weather, occurrence	Australia	Increase in fire danger* across the country (less than 10% up to 200%).	Present *v.* high/low emission for 2050/2100	+	Pitman *et al*. 2007
Area burned	Canada (boreal forest in Alberta)	12.9% or 29.4% increase.	$2 \times CO_2/3 \times CO_2$	+	Tymstra *et al*. 2007
Area burned, occurrence	USA (Alaska) and western Canada	Area burned: 2 or 3.5–5.5 times. Fire occurrence: fire return intervals will decrease 50% in Alaska (87–103 years less between fires) and 40% in western Canada (64–69 years less).	Reference 1970–2000 *v.* 2041–50/2091–2100 for area burned; 2070–2100 for occurrence	+	Balshi *et al*. 2008
Occurrence	Canada (Southern Boreal Shield)	Increase of 34–61% in the typical number of large fires.	1795–1998 *v.* 1999–2100	+	Girardin and Mudelsee 2008
Area burned	USA (California)	9–15% increase (depending on scenario).	Reference 1895–2003 *v.* 2050–99	+	Lenihan *et al*. 2008
Fire weather, occurrence	Russia (boreal forest)	Increase in the number of days with high fire danger* of up to 12 days, depending on location; areas of maximum fire danger risk will double by 2050.	1981–2000 *v.* 2100	+	Malevsky-Malevich *et al*. 2008

(*Continued*)

Table 1. (Continued)

Fire activity metric	Location	Projected change	Time period or scenario	General trend	Reference
Fire weather, seasonality, intensity	Canada (south-central British Columbia)	Fire season: 30% increase in fire season length. Fire weather: severity will increase by 95% during summer months. Fire intensity: shift from surface fire–intermittent crown fire regimes (high intensity) to a predominantly intermittent–full crown fire regime (extremely high intensity).	Current *v.* 2070	+	Nitschke and Innes 2008
Area burned	USA (California)	Increase in the number of large fires in most areas of CA (12–90%) except for one area of decrease (−29%) (range depends on different scenarios).	2070–99 *v.* 1961–90	+	Westerling and Bryant 2008
Area burned, severity	Canada (boreal forest)	Area burned: increase by 1/3 (2 × CO_2); double (3 × CO_2). Fire severity: increase 0–18%.	2 × CO_2; 3 × CO_2	+	Amiro *et al*. 2009
Area burned	Canada (Quebec)	Increase in area burned of ~1.2 to 8.0 times (depending on scenario).	1959–99 *v.* 2100	+	Drever *et al*. 2009
Occurrence	Global	Fire-prone areas will increase in some areas and decrease in others (highly variable – see paper).	1996–2006 *v.* 2010–39, 2040–69, 2070–99	±	Krawchuk *et al*. 2009*a*
Area burned, occurrence	Canada (mixedwood boreal forest of central-eastern Alberta)	Area burned: 1.9 (2 × CO_2) and 2.6 (3 × CO_2)-fold increases. Fire occurrence: 1.5 (2 × CO_2) and 1.8-fold (3 × CO_2) increase of lightning fire initiation.	Reference 1975–85 *v.* 2040–49 (2 × CO_2)/ 2080–89 (3 × CO_2)	+	Krawchuk *et al*. 2009*b*

*For the purposes of this Table, fire danger has been included as fire weather and fire occurrence.

the tropics, driven largely by deforestation and agricultural development in South America and South-east Asia (Cochrane 2003; Carmona-Moreno *et al*. 2005). Burned area has increased slightly in the circumpolar boreal forest and western forests of the USA, possibly due in part to increased fuel loads from successful past suppression in North America and decreased fire suppression funding in Russia (Gillett *et al*. 2004; Mouillot and Field 2005; Westerling *et al*. 2006). In contrast to the early decades of the 20th century when fire commonly occurred in temperate forests, temperate fire is now strongly influenced by population density, landscape pattern, prescribed fire, and fire prevention policy. For example, area burned has increased in southern Europe as a result of changes in agricultural policy causing rural exodus and establishment of forest and shrubland on abandoned land (Mouillot and Field 2005). Australia continues to be the 'fire continent', although fire in temperate forests and savannas has remained constant or slightly decreased during the last few decades.

Northern- and southern-hemisphere fire seasons follow distinct patterns as much of the anthropogenic fire occurs during seasonal dry periods (Carmona-Moreno *et al*. 2005). Both hemispheres show burning maxima occurring at more than one time each year. Climate variability causes spatial and temporal shifts in fire seasonality in some regions, but fire season is very consistent and stable in other regions. Although there is very strong annual periodicity, there is also a substantial interannual variation in both hemispheres that follows a 4-year pattern and correlates well with El Niño–Southern Oscillation events (Carmona-Moreno *et al*. 2005; Le Page *et al*. 2008).

Fire and carbon emissions

Fire affects the carbon balance of terrestrial biomes through its influence on the immediate release of carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO) during combustion of fuels (Cofer *et al*. 1998; Rinsland *et al*. 2007) and the carbon dynamics of post-fire vegetation. The latter includes the slow release of CO_2 by decomposing dead organic matter, and the photosynthetic CO_2 uptake by new vegetation. As the carbon sequestration rate increases as vegetation grows (Amiro 2001; Litvak *et al*. 2003), fire affects the landscape carbon balance by modifying vegetation age-class structure (Kurz *et al*. 2008). Overall, the large-scale forest carbon balance remains stable as long as fire regime is unchanged, but any shift in fire regime will directly impact long-term forest carbon storage (Balshi *et al*. 2008).

The effect of fire on carbon balance varies among biomes. Fire is the primary driver of landscape carbon balance in the boreal forest (Harden *et al*. 2000; Bond-Lamberty *et al*. 2007), a region that represents 1/5 of global vegetation cover (Mouillot and Field 2005) and 1/3 of terrestrial carbon storage (Apps *et al*. 1993; Zoltai and Martikainen 1996). There are 337 Mha of peatlands within the circumpolar boreal region containing 397–455 Pg of carbon, which are at risk of greater carbon release with climate change by several processes including increased wildfire (Zoltai *et al*. 1998; Turetsky *et al*. 2002). Annual carbon emissions from tropical wildfires are extremely variable but they can represent a large global contribution when tropical peatlands burn (Cochrane 2003), such as when peatland fires in Indonesia released 0.81–2.57 Gt of carbon during the 1997–98 El Niño (Page *et al*. 2002). Africa is the largest wildland fire carbon emitter owing to frequent and extensive burning of grasslands and savannas, accounting for ~49% of total global wildland fire carbon emissions. South America (13%), equatorial Asia (11%), boreal forest (9%) and Australia (6%) account for most of the remainder (van der Werf *et al*. 2006).

Annual global carbon emission estimates by wildland fire are quite variable, ranging from 1410 to 3139 Tg of carbon per year (Schultz *et al*. 2008), with an average of 2078–2460 Tg carbon per year (Lavoué *et al*. 2000; van der Werf *et al*. 2006; Schultz *et al*. 2008). This is equivalent to 26–31% of current global CO_2 emissions from fossil fuels and industrial processes (Raupach *et al*. 2007). Feedbacks from global fire emissions have the potential to be a major factor in our changing climate. There is the possibility of a positive feedback occurring, whereby a warmer and drier climate will create conditions conducive to more fire. This in turn will increase carbon emissions from fires, which would feed the warming (Lavorel *et al*. 2006). Wildfires also contribute to atmospheric warming through black carbon emissions, which are the second strongest contribution to current global warming after CO_2 (IPCC 2007). Open biomass burning associated with deforestation and crop residue removal produces ~40% of global black carbon emissions (Bond *et al*. 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). However, it has been suggested that the net effect of fires may not result in a positive feedback to climate when the effects of greenhouse gases, aerosols, black carbon deposition, and changes in albedo are taken into account over a longer time period (Randerson *et al*. 2006).

Wildland fire – key factors

Fire activity is strongly influenced by four factors: fuels, climate–weather, ignition agents and people (Flannigan *et al*. 2005). The fuel type, continuity, structure, moisture, and amount are critical elements of fire occurrence and spread. Cumming (2001) illustrates that fuel type affects what parts of the landscape are burned in Canadian boreal forests. For fires to spread, there needs to be fuel continuity; some suggest that at least 30% of the landscape needs to have fuel for a fire to spread (Hargrove *et al*. 2000). This is important in many drier parts of the world where sufficient precipitation is required during the season (wet season or winter) preceding the fire season for the growth of sufficient fuels to be available to carry fire on the landscape (Swetnam and Betancourt 1998; Meyn *et al*. 2007). Fuel structure can also be important in fire dynamics, for example, understorey shrubs in a forest can act as ladder fuels that carry a surface fire up into tree crowns and generate a much more intense fire. Krawchuk *et al*. (2009*a*) found that net primary productivity, as a metric of flammable vegetation, best explained the distribution of global fire, with additional variation being explained by the interplay of temperature and precipitation producing climate–weather conditions conducive to fire. Fuel heterogeneity may be the key determinant in some regions; for example, when looking at annual fire initiation in the mixed boreal forest of Alberta, Krawchuk *et al.* (2006) found forest composition explained more variation than weather indices. The relative influence of fuel and weather on fire activity likely varies with scale and biophysical heterogeneity in a given study system. Although the amount of fuel, or fuel load, affects fire activity as a minimum amount of fuel is required for fire to start and spread, fuel moisture largely determines fire behaviour, and has been found to be an important factor in the amount of area burned (Flannigan *et al.* 2005). Many of these individual factors can be summarized by generalized fuel type classifications.

Weather and climate – including temperature, precipitation, wind, and atmospheric moisture – are critical aspects of fire activity. For example, Cary *et al.* (2006) found that weather and climate best explained model area burned estimated from landscape fire models compared with variation in terrain and fuel pattern. Carcaillet *et al.* (2001) found that climate was the key process triggering fire over the eastern boreal forest during the Holocene. Prasad *et al.* (2008) found that mean annual temperature and average precipitation of the warmest quarter of the year were among the variables that best explained fire occurrence in southern India.

Numerous studies suggest that temperature is the most important variable affecting wildland fire, with warmer temperatures leading to increased fire activity. Gillett *et al.* (2004) suggest that the increase in area burned in Canada over the past four decades is due to human-caused increases in temperatures. The reason for the positive relationship between temperature and wildland fire is three-fold. First, warmer temperatures will increase evapotranspiration, as the ability for the atmosphere to hold moisture increases rapidly with higher temperatures, thereby lowering watertable position (Roulet *et al.* 1992) and decreasing fuel moisture unless there are significant increases in precipitation. Second, warmer temperatures translate into more lightning activity that generally leads to increased ignitions (Price and Rind 1994). Third, warmer temperatures may lead to a lengthening of the fire season (Westerling *et al.* 2006). While testing the sensitivity of landscape fire models to climate change and other factors, Cary *et al.* (2006) found that area burned increased with higher temperatures. This increase was present even when precipitation was high, although the increase in area burned was greatest for the warmer and drier scenario. Precipitation is also an important variable in fire activity but timing of precipitation during the fire season rather than the amount is usually the most important aspect (Flannigan and Harrington 1988).

Fire activity is strongly influenced by conditions throughout the atmosphere as well as the conditions at the earth's surface. Temperature, precipitation, wind, cloudiness and atmospheric pressure depend largely on the horizontal and vertical state of the atmosphere. The strength, location and movement of surface highs and lows and associated warm or cold fronts are functions of the three-dimensional atmosphere. Often, the term 'blocking ridges' has been associated with fire outbreaks. These are persistent ridges in the upper atmosphere (usually at the 500-mb (500-hPa) level, which is ~5500 m above sea level) that last a week or longer. These ridges are a feature in the mid and high latitudes where westerly upper flow prevails. They tend to block or divert precipitation-bearing systems to the north or south of the ridge; thus, dry and warm weather at the surface is typically associated with these upper ridges. Newark (1975) discovered that 500-mb (500-hPa) long-wave ridging was related to forest fire occurrence in north-western Ontario during the summer of 1974. Flannigan and Harrington (1988) found that the 700-mb (700-hPa) height anomaly for the provincial forested regions was the predictor that was selected most often when relating meteorological variables to monthly provincial area burned in Canada during 1953–80. Johnson and Wowchuk (1993) found that blocking ridges were related to large-fire years in the southern Canadian Rocky Mountains, whereas negative anomalies were related to small-fire years. Skinner *et al.* (1999) found that 500-mb (500-hPa) height anomalies were well correlated with seasonal area burned over various large regions of Canada and Alaska. Research suggests that blocking frequency is related to the wave number (the number of long waves in the westerlies – typically three to five), with blocking ridges being more frequent with higher wave numbers (Weeks *et al.* 1997). Pereira *et al.* (2005) have also demonstrated this phenomenon in Portugal, as did Gedalof *et al.* (2005) in the western United States. Research has suggested that the persistence of blocking ridges in the upper atmosphere will increase in a doubled carbon dioxide situation ($2 \times CO_2$) (Lupo *et al.* 1997).

Large-scale, recurring variability in ocean and atmosphere circulation patterns, known as teleconnections or synoptic-scale circulation patterns, occur on a multiannual to multidecadal time scale (Troup 1965; Zhang and Battisti 1997; Le Goff *et al.* 2007; Le Page *et al.* 2008). Many oscillation patterns have been identified around the world, including the El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Arctic Oscillation (AO), and the Atlantic Multidecadal Oscillation (AMO). These teleconnections are associated with systematic variations in temperature, precipitation, air pressure, humidity, wind patterns, and dry lightning occurrence over large areas (Girardin *et al.* 2006; Trouet *et al.* 2008). Considering the close relationship between climate and wildfire, it follows that many studies have revealed that large-scale patterns and synchronization of wildfire activity are related to these oscillations. For example, Johnson and Wowchuk (1993) observed that blocking ridges associated with large-fire years are teleconnected to upper-level troughs in the North Pacific and eastern North America, which is the positive mode of the Pacific North American (PNA) pattern. Furthermore, relationships between fire frequency, extent, seasonality, and area burned and ENSO have been discovered in global studies (Carmona-Moreno *et al.* 2005; Le Page *et al.* 2008) and studies from almost all parts of the world including North America (Simard *et al.* 1985; Swetnam and Betancourt 1990; Chu *et al.* 2002; Román-Cuesta *et al.* 2003; Westerling and Swetnam 2003; Fulé *et al.* 2005; Macias Fauria and Johnson 2006; Skinner *et al.* 2006; Kitzberger *et al.* 2007; Trouet *et al.* 2008), South America (Kitzberger 2002; Alencar *et al.* 2006; González and Veblen 2006), Eurasia (Siegert *et al.* 2001; Fuller and Murphy 2006; Balzter *et al.* 2007), Australia (Verdon *et al.* 2004), and Africa (Riaño *et al.* 2007). Kitzberger *et al.* (2007) found that for the Pacific North-west of North America, warm and dry conditions are associated with the

El Niño phase of ENSO. These conditions generally cause earlier spring snow melt over large areas, and thus an extended and synchronized fire season across the entire region. Conversely, in the American South-west, they discovered warm and wet conditions are related to El Niño events, resulting in an increase in vegetation growth. This new growth is potential fuel for when a drought period (La Niña) occurs. Thus, when an El Niño is followed by a La Niña in the South-west, widespread and severe fires occur. Balzter *et al*. (2007) found that both the AO and ENSO in Siberia impact the timing of the vegetation growing season and are therefore indirectly related to burned area. Therefore, teleconnections can impact wildfires through direct effects on fire weather and indirect effects of climate on vegetation growth, seasonality, and composition.

Emissions from wildfires can also be affected by synoptic-scale circulation patterns. For example, in Indonesia during an El Niño phase of the ENSO, higher levels of air pollution were found during forest fires owing to the lack of moisture in the air that would remove the particulate matter (Heil *et al*. 2006). Another factor to be considered is the long-range transport of forest fire emissions. A study done by Spichtinger *et al*. (2004) revealed that the intercontinental transport of pollutants can have drastically different pathways during ENSO events. Lastly, intense wildland fires can generate pyrocumulonimbus (fire-generated thunderstorms that develop in the convection column) that can inject smoke in the troposphere and stratosphere. Smoke in the stratosphere can have hemispheric impacts for 3 months or longer in terms of stratospheric temperature and tropopause height (Fromm *et al*. 2008).

Specific mechanisms behind the relationship between teleconnections and wildfire are yet to be elucidated, and there is still significant work to be done to be able to use these climatic variations to provide long-range fire activity forecasts for planning purposes (Swetnam and Betancourt 1990, 1998; Chu *et al*. 2002; Kitzberger 2002; Skinner *et al*. 2006; Kitzberger *et al*. 2007; Le Goff *et al*. 2007; Trouet *et al*. 2008). Additional study needs to be done to examine how these teleconnections may change in the future and how this, in turn, will affect wildfires (McKenzie *et al*. 2004; Macias Fauria and Johnson 2008; Müller and Roeckner 2008).

Appropriate weather conditions are an essential element required for wildland fire to occur. Where fuel is readily available, weather is the most important factor for fire activity in many parts of the world. Its importance lies in generating fire-conducive conditions such as low fuel moisture and winds, as well being a key factor in the occurrence of lightning, a primary ignition agent. Complex patterns of global fire activity can largely be explained in terms of large-scale climate controls modulated by local changes in vegetation (Power *et al*. 2008). Fire can occur without humans and indeed fire was prevalent in prehistoric times (Marlon *et al*. 2008), but people play a major role in current fire activity.

People and fire

People have lived with and exploited fire for all of our history, and our fire problems are essentially socially constructed problems (Pyne 2007). Most global fire is the human application of fire on the landscape. This is reflected by over 80% of global fire occurring in tropical grasslands and savannas (Mouillot and Field 2005; van der Werf *et al*. 2006) and historical changes in fire patterns tracking human activity (Marlon *et al*. 2008). For example, fire is commonly used for removal of agricultural debris and pasture maintenance in the tropics and other regions (Goldammer 1990; FAO 2007). The rate of burning in tropical forests increased exponentially over recent decades as fire was used in deforestation for agricultural expansion (Mouillot and Field 2005). Because people continue to be the main source of wildland fire in almost all global regions, people are also by far the main cause of fires having negative impacts on the environment and society (FAO 2007). Most fire is intentional, but because many fires are poorly controlled, some fires escape intended boundaries to become disaster events, or megafires. There has been an epidemic of megafires that have occurred around the world during the last 15 years (Pyne 2007). In addition to climate change driving this recent phenomenon, contributing human factors include biomass burning associated with land clearing, increasing available fuel loads caused by land abandonment (afforestation, revegetation), fuel build-up from historical fire suppression (e.g. Australia, western North America), and people as a globally omni-present ignition source (Prestemon and Butry 2005; Genton *et al*. 2006; FAO 2007).

The estimated social and economic costs of wildland fire are known to be huge, but are largely unquantified (FAO 2007). Direct suppression costs would easily be many billions of dollars. Wildland fires can have many serious negative impacts on human safety (Viegas 2002) and health (US EPA 2004), regional economies (e.g. Glover and Jessup 1999), and global climate change (Crutzen and Goldammer 1993; Kasischke and Stocks 2000). These include loss of human life, loss of livelihood (e.g. animals) and property, and indirect costs of settlement evacuations (FAO 2007). However, fire is a natural, ecologically desirable, and essential agent in many ecosystems. After a period of attempted fire exclusion revealed this as an economically and physically impossible goal in many regions; modern fire management agencies now strive to balance the need to protect life, property, and industrial and recreational interests with the ecological need for landscape-scale fires.

Although uncontrolled wildfires are an immediate threat to the safety of nearby communities, the negative short- and long-term health impacts associated with fire emissions are equally serious and much more far-reaching owing to long-range transport of pollutants (Heil and Goldammer 2001; Goldammer *et al*. 2009). Wildland fires release many pollutants into the atmosphere that are significantly related with adverse health effects (Kunii *et al*. 2002; Sastry 2002; Fowler 2003; Rittmaster *et al*. 2006; Schultz *et al*. 2008; Goldammer *et al*. 2009). In particular, epidemiological studies show elevated levels of particulate matter $<2.5\,\mu m$ ($PM_{2.5}$) are correlated with respiratory problems, pneumonia, chronic obstructive pulmonary disease, heart disease, stroke, and premature mortality (US EPA 2004). Mercury (Hg) is another pollutant that poses a serious public health risk (Mahaffey 1999). Northern forests and peatlands have experienced drastically increased Hg accumulation rates during recent industrial times (Turetsky *et al*. 2006). In Canada, boreal fires release large amounts of Hg; this is equivalent to $\sim$30% of the global anthropogenic Hg emissions in an average year, and near 100% in extreme years (Sigler *et al*. 2003; Turetsky *et al*. 2006).

Future fire activity

Fire activity including area burned, fire occurrence, fire season, fire intensity, and fire severity respond dynamically to the climate–weather, fuels, and people. Recently, our climate has been warming as a result of increases of radiatively active gases (CO_2, CH_4, etc.) in the atmosphere caused by human activities (IPCC 2007). Such warming is likely to have a rapid and profound impact on fire activity (Scholze *et al*. 2006; Krawchuk *et al*. 2009*a*), as will potential changes in precipitation, atmospheric moisture, wind, and cloudiness (Flannigan *et al*. 2006; IPCC 2007). Vegetation patterns, and thus fuels, will change in the future owing to both direct effects of climate change and indirectly as a result of changing fire regimes (Soja *et al*. 2007). Humans will continue to be a crucial element of fire activity in the future through fire management, human-caused fire ignitions, and land-use. In the future, changes in climate–weather, fuels, and people and the non-linear, complex and sometimes poorly understood interactions among these factors will determine fire activity. Table 1 summarizes the literature with respect to the potential future fire weather, area burned, fire occurrence, fire season, fire intensity, and fire severity throughout the world.

Fire weather

Fire weather is defined as the weather variables that influence fire behaviour, starts, and suppression. These variables include temperature, precipitation, humidity, and wind. These weather factors are predicted to change for much of the world (IPCC 2007), and thus fire weather can be expected to be affected by climate change.

Table 1 outlines work done on predicting future fire weather around the world. Studies out of Australia have found that generally fire weather will increase across the country, though there is large spatial variability. Based on two different GCMs (global circulation models), Beer and Williams (1995) found that in doubled CO_2 conditions, most of Australia will see at least a 10% increase in fire danger conditions, with some areas of decreases. Another study using similar methods predicted that fire danger will increase 10–30% across Australia (Williams *et al*. 2001). Pitman *et al*. (2007) found that for the peak month of Australia's fire season, fire danger may increase between $<10\%$ and up to 200%, depending on area. These future changes in fire danger in Australia were explained mostly by a decrease in relative humidity and an increase in temperature.

Future fire weather for the Mediterranean has also been forecast to increase by Moriondo *et al*. (2006) using an RCM (regional climate model) and two different emission scenarios. They found that there will be more days with higher Fire Weather Index (FWI; a component of the Canadian Forest Fire Weather Index System that provides a rating of fire danger based temperature, humidity, wind speed, and precipitation) values (i.e. greater than 45), and there will be an increase in extreme fire weather periods (i.e. high FWI value for 7 or more days in a row). They suggest that the changes may have the most impact in areas with significant forest cover.

The circumpolar boreal forest covers 1.2 billion hectares in northern Eurasia and North America (Soja *et al*. 2007). Stocks *et al*. (1998) expect more extreme fire weather in a $2 \times CO_2$ climate due to a projected increase in fire weather severity across the circumpolar boreal. The most drastic increases are to be in the south of Canada's prairie provinces and in southern Russia. A similar study by Flannigan *et al*. (1998) found that the FWI in the boreal forest will change in the future, but the changes are spatially dependent. Their study found FWI values may decrease in eastern Canada, western Canada, and most of northern Europe (Sweden, Finland, and western Russia); increases are expected in southern Sweden and Finland and throughout central Canada, where the most extreme increase were seen. Another study focussing on the Canadian boreal forest found that the FWI will decrease for some of eastern Canada, but increase for most of the rest of the country in a $2 \times CO_2$ climate (Flannigan *et al*. 2001). In the Russian boreal forest, it has been predicted that areas of maximum fire danger risk will double by 2050, and changes will vary spatially across the country (Malevsky-Malevich *et al*. 2008).

The majority of work on future fire weather has been done in North America. The FWI in Canada is expected to increase, but with significant regional variation (Bergeron and Flannigan 1995; Amiro *et al*. 2001). The most extreme increases have been found to be in central and western Canada, and some decreases have been predicted for parts of Quebec, Alberta, and northwestern Canada (Bergeron and Flannigan 1995; Amiro *et al*. 2001). Brown *et al*. (2004) found that in the western USA, there may be an increase in the number of days with high fire danger by 2089 due to significant decreases in relative humidity. In California, it is predicted that the incidence of high coastal winds during the latter part of the fire season (when there is generally extremely dry fuel) will increase, resulting in very extreme fire weather (Miller and Schlegel 2006). Fire weather severity, as measured by the daily severity rating (DSR; a component of the Canadian Forest Fire Weather Index System that provides a rating of daily fire control difficulty based on the FWI), or the seasonal severity rating (SSR; similar to the DSR except it represents an entire fire season), is predicted to rise according to several studies. Flannigan and Van Wagner (1991) used three GCMs to model future SSR in a $2 \times CO_2$ climate and found that there will be a 46% increase across Canada due to increasing temperature, decreasing humidity, and changing precipitation patterns. A similar result was found by Flannigan *et al*. (2000), with a 10–50% increase in SSR over most of North America. In a $3 \times CO_2$ situation, SSR in north-west Canada is predicted to increase 19–44%, depending on the model used and the specific location (Kochtubajda *et al*. 2006). Nitschke and Innes (2008) found that DSR will increase up to 95% during the summer months by 2070.

Overall, the studies done on potential future changes in fire weather across the world show that the changes in fire weather will be spatially variable, and these changes have the potential to be extreme. More studies need to be done to fill in research gaps and refine predictions for fire weather. For example, no studies that we know of have been done in Africa, large parts of Eurasia, and South America.

Area burned

The long-term average of area burned across a landscape is determined by a complex set of variables including the size of the sample area, the period under consideration, the topography, fragmentation of the landscape (rivers, lakes, roads, agricultural land), fuel characteristics, season, latitude, fire suppression policies and priorities, fire control, organizational size and efficiency, fire site accessibility, ignitions (people and lightning), and simultaneous fires, as well as the climate–weather. Many studies have addressed the impact of climate change on fire weather severity (see Table 1), but a much smaller number of papers have addressed area burned. Flannigan and Van Wagner (1991) compared SSR from a $2 \times CO_2$ scenario (mid-21st century) with the $1 \times CO_2$ scenario (approximately present day) across Canada. The results suggest increases in the SSR across all of Canada, with an average increase of nearly 50%, translating roughly into a 50% increase of area burned. Price and Rind (1994) suggest that lightning-caused fires in the United States will increase by 44% by the end of the 21st century, while the associated area burned would increase by nearly 80% according to GCM predictions. Using an initial-attack suppression model with GCM output, Fried *et al.* (2004) estimate future changes in area burned by contained fires may range from a 41% increase for the San Francisco Bay area and the Sierra Nevada to an 8% decrease for the north coast of California. Bergeron *et al.* (2004) suggest increases in area burned for most sites across Canada by the middle or end of this century, although some sites in eastern Canada were projected to have no change or even a decrease. Area burned was projected to increase by as much as 5.7 times the present values, but for many sites, the historical area burned (1600s to near present) was higher than estimated future fire activity. This comparison emphasizes the need to temper our thoughts on changes in fire to include a broad temporal context. Flannigan *et al.* (2005) used historical relationships between weather, fire danger and area burned in tandem with two GCMs to estimate future area burned in Canada and suggest an increase of 74–118% in area burned by the end of this century. Using the dynamic global vegetation model (DGVM) MC1 to examine climate, fire and ecosystem interactions in Alaska, Bachelet *et al.* (2005) suggest area burned increases of 14–34% for 2025–99 relative to 1922–96. Lenihan *et al.* (2008), also using the MC1, simulated vegetation distribution, carbon and fire in California with three future climate scenarios. They estimated area burned increases of 9–15% above the historical average by the end of this century for all three scenarios. In northern Alberta, Canada, Tymstra *et al.* (2007) suggest area burned increases of $\sim$13 and 29% for $2 \times$ and $3 \times CO_2$ scenarios relative to the $1 \times CO_2$ scenario using a fire growth model with output from the Canadian RCM. Using air temperature and fuel moisture codes from the Canadian Forest Fire Weather Index System, Balshi *et al.* (2008) suggest decadal area burned for western boreal North America will double by 2041–50 and will increase in the order of 3.5 to 5.5 times by the last decade of the 21st century compared with 1991–2000. Amiro *et al.* (2009) predict that in a $3 \times CO_2$ situation, area burned will double from current levels in the Canadian boreal forest. Almost all studies to date have focussed on North American locations (see Table 1). However, Cardoso *et al.* (2003) predict an increase in area burned due to a changing climate in South America under two different deforestation scenarios. Thonicke and Cramer (2006) investigated future fire activity in Germany and expect area burned to decrease, but there may be slight increases depending on the GCM scenario used.

There is a great deal of variability in the results of these studies, as would be expected given different study areas and approaches used, as shown in Table 1. This variation highlights the need to view the impact of climate change on area burned in a spatially dependent context. Most studies suggest increases in area burned with climate change and this is consistent with recent and longer-term historical trends (Mouillot and Field 2005; FAO 2007; Power *et al.* 2008). However there were some areas with no change projected or even a decrease in area burned, illustrating that global fire activity changes will be heterogeneous.

Fire occurrence

Similarly to area burned, changes in climate will influence the future occurrence of wildfire through myriad pathways that involve weather conditions conducive to combustion, fuels to burn and ignition agents. As humans manage fire in most parts of the world, the resulting changes in fire occurrence patterns will also be contingent on human activity, government policies, and social goals.

Fire occurrence is a relatively simple measure of fire activity that quantifies the presence or absence of an event. Here, we define fire occurrence analogously to fire initiation: the sustainability of flaming ignition that results in the origin and detection of a fire. A fire occurrence is the starting point from which a fire can grow to be large or alternatively extinguished, either through direct suppression or without human intervention. Where, when, and why fires occur will be critical to ecological, atmospheric, societal, and management reactions to climate change. Fire occurrence is particularly critical to fire management because in high-value areas where fire exclusion is the goal, getting suppression resources to fires while they are small is of paramount importance. It is when large numbers of fires occur over a short time period that a management agency can become overwhelmed and not be able to take action on new starts. It is during these times that fires have highest probability of escaping and burning significant areas.

The direct effect of climate change on fire occurrence will be through fire weather, as it affects the moisture content and sustained ignition of fuel. Although overall global temperature is projected to rise in the future, there will be considerable heterogeneity in the effect of climate change on fire weather and fire weather indices through the interplay of precipitation and temperature. As already illustrated, there are areas where fire weather severity during the burning season is expected to increase from recent historical conditions, as well as areas where no change or even a decrease is expected (Table 1). Studies focussed on future fire weather illustrate potential alteration of fire activity; however, explicit projections of future occurrence gets us even closer to understanding the influence of global climate change on fire. In regions of the globe where available (burnable) fuels are abundant, such as forests or shrublands, a reasonable method to project future fire occurrence is to relate observed fires (either human-caused or lightning-caused) and fire weather conditions with statistical models, then use the parameters of the model with climate data from GCMs or RCMs to project fire occurrence in the future. The relationship between moisture content of fuels as influenced by weather, and the basic sustainability of flaming ignition has been quantified in many different types

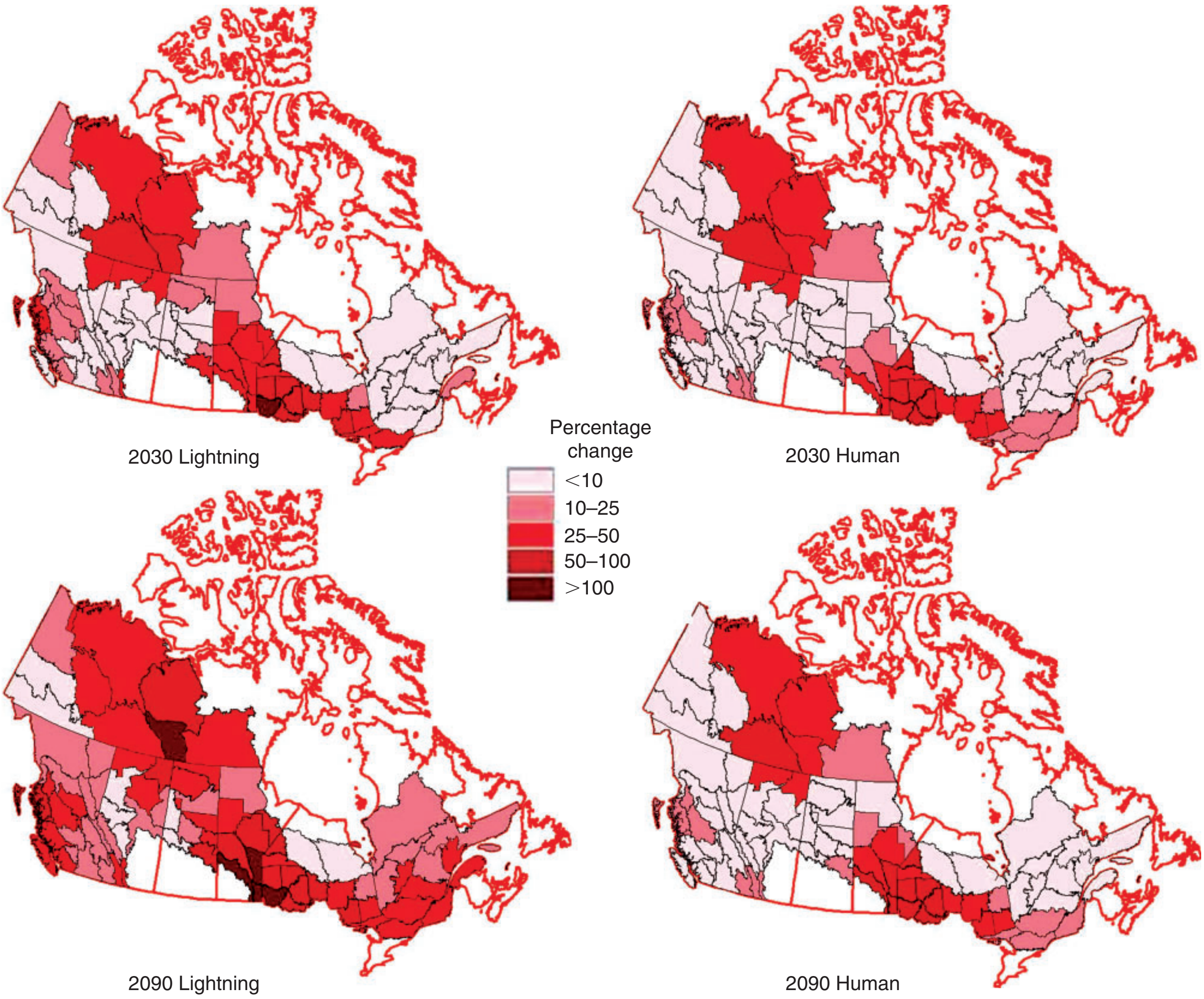

Fig. 4. Relative change (percentage increase) in fire occurrence between future and baseline scenarios for the Canadian Climate Centre GCM (global circulation model). Relative change is given as the percentage increase in number of fires predicted by the GCM (future scenario minus baseline scenario) divided by the total number of fires in the baseline scenario (i.e. $(n_{2020\text{–}40} - n_{1975\text{–}95})/n_{1975\text{–}95}$); 'no data' is shown in white.

of ecosystems in countries around the world: the United States (Blackmarr 1973), Finland (Larjavaara *et al.* 2004), Indonesia (de Groot *et al.* 2005), Portugal (Fernandes *et al.* 2002), and Canada (Lawson *et al.* 1997). Similarly, many studies have examined the influence of fire weather and fuel moisture on fire occurrence itself (Martell *et al.* 1987, 1989; Vega-Garcia *et al.* 1995; Mandallaz and Ye 1997; Preisler *et al.* 2004, 2008; Wotton and Martell 2005; Drever *et al.* 2006; Krawchuk *et al.* 2006). There are few studies that have used these fire–weather relationships to then project future fire occurrence. For example, in Alberta, Canada, Krawchuk *et al.* (2009*b*) projected regional increases in lightning-caused fire occurrence in the mixedwood boreal forest through the 21st century, showing an expected 80% increase in initiation. Wotton *et al.* (2003) projected an increase in human-caused fires in Ontario of 50% by the end of the 21st century in association with climate change. Though an overall increase in fire was projected, there were areas within these regions with less severe conditions and reduced fire occurrence. At a much broader scale, both human- and lightning-caused fire was examined across the entire forested area of Canada and the results suggest that there is significant regional variation in the change in future fire occurrence rates compared with current levels (B. M. Wotton, pers. comm.) (Fig. 4). Fire occurrence in the boreal forest of Russia has been predicted to increase, with up to 12 more days per year with high fire danger (a component of which is fire occurrence) (Malevsky-Malevich *et al.* 2008). At a global scale, Krawchuk *et al.* (2009*a*) used projected changes in climate to estimate changes in fire occurrence and proposed that increases and decreases in fire occurrence could lead to a relatively small net global change in fire occurrence. This work focussed only on occurrence and was not able to include changes in other parameters such as fire severity, vegetation or land–atmosphere feedbacks. Global analyses on fire frequency by Scholze *et al.* (2006) using a DGVM and climate change data also suggest a large spatial variability in future global fire occurrence, with areas of decreases and areas of increases.

The interaction between weather and fuels and their influence on fire activity can be viewed as a continuum between energy-limited and moisture-limited landscapes. Energy-limited parts of the world are locations where fuel is always abundant, such as forests or shrublands, but temperatures (energy) conducive to fire limit its occurrence (see Meyn *et al*. 2007). In contrast, moisture-limited parts of the world are those where weather conditions are conducive to fire, but there is insufficient fuel available (Meyn *et al*. 2007; Westerling and Bryant 2008). These are referred to as moisture-limited because availability of precipitation during the growing season preceding the fire season affects the growth and accumulation of fuel, and therefore the subsequent likelihood of fire. On the energy-limited end of the range, we would find the northern boreal forests, whereas the moisture-limited end of the range would be desert ecosystems. The humid tropical rainforests are an interesting case of energy limitation whereby, in the absence of human intervention, the high humidity levels maintained by the forest canopy result in a biomass-rich, energy-limited system. The effects of climate change on fire occurrence will manifest themselves in different ways across this gradient of energy-limited to moisture-limited landscapes.

The distinction of moisture-limited areas, where climate change can have near-term effects on the availability of fuels, is also relevant for interpreting the discussion of Weber and Flannigan (1997) on boreal forest fire activity and climate change. They suggest fire will be most dominantly affected by direct changes in fire season weather, and that indirect alteration of fire activity through changes in vegetation will occur relatively slowly. This may be true for the energy-limited areas such as the boreal forest, where species are long-lived, have limited dispersal, and climate-related change in species ranges is expected to be slow (Clark *et al*. 1998). However, in those areas of the world where decreased precipitation and increased temperature can reduce productivity or increased precipitation can result in high productivity of flammable grasses, such as in deserts and shrublands, climate change in association with the rapid advance of invasive species (e.g. D'Antonio and Vitousek 1992; Brooks *et al*. 2004) will alter vegetation structure (composition, configuration, and connectivity) and have strong, indirect effects on fire occurrence in both the near and distant future.

The combined effects of climate changes on fire occurrence via fire weather conditions and vegetation have been explored using climate–soil–vegetation simulation models. Mouillot *et al*. (2002) show that changes in the rate of fire occurrence associated with climate change could result in reduced fire return intervals that alter community composition in mixed maquis shrubland and forested landscapes of France. Hoffmann *et al*. (2002) predict that fire frequency will increase in tropical savanna areas of South America, Africa, and Australia in the future with land-cover and climate change, and climate feedbacks to land-cover changes. Schumacher and Bugmann (2006) assessed the interactions between forest dynamics, climate change, and fire in the Swiss Alps and suggest that increased fire occurrence may lead to a drastic change in plant community composition. Bachelet *et al*. (2003, 2005) demonstrate varying degrees of climate-driven changes in vegetation, weather, and fire activity across the United States depending on both the vegetation model used and climate data driving the simulation. Bachelet *et al*. (2003) emphasize that with the current state of the DGVMs, only broad patterns of fire should be interpreted, because the representation of fire location and timing is limited.

The majority of wildfires are ignited by lightning or humans; volcanoes start few fires and only in selected parts of the world. Lightning-caused fire contributes to the majority of fire occurrence in relatively few parts of the world, such as remote areas of boreal North America (Stocks *et al*. 2003), tropical savannas and seasonal forests (Goldammer and Price 1998). Price and Rind (1994) indicate that climate change may increase the number of lightning fires over the United States by 44% under $2 \times CO_2$ conditions, that the largest changes in moisture balance and lightning activity will be in the tropics, with a 72% increase in cloud-to-ground lightning over continental regions. Nevertheless, humans are the main agents of fire across most of the planet. Changes in climate may have little direct influence on human behaviour; however, changes in vegetation, fuel moisture and fire weather caused by climate change may alter the ease of fire ignition and success of fire suppression by humans. Changes in fire-related policy including development in the wildland–urban interface, fire management in wilderness areas, social awareness of fire risks, and forest and agricultural management will have very large impacts on human-caused fire occurrence alongside global climate change (Moritz and Stephens 2008). Changes in human behaviour are particularly relevant in the Amazon, where large areas of tropical forest that has rarely burned in the past are coaxed to burn for land-clearing, leading to grazing and croplands (Nepstad *et al*. 1999; Cardoso *et al*. 2003; Cochrane 2003), promoted by recent drought and expectations that drought conditions will continue in the future (Aragão *et al*. 2007).

Fire season

Globally, no distinct or common fire season exists. Although individual regions tend to have a distinct 'high' or 'active' fire season, satellite reconstruction of hot spots due to wildfire (e.g. Carmona-Moreno *et al*. 2005) reveal there is always fire activity somewhere on the planet (see Fig. 1). Thus, the impacts of climate change on fire season cannot be generalized to any simple single expected outcome, but must be considered based on regional weather and vegetation and importantly the interaction between these factors.

Fire activity in savanna areas such as central Africa and northern Australia can be quite strongly linked with precipitation, tracking the dry season throughout the year (Cahoon *et al*. 1992; Carmona-Moreno *et al*. 2005). Fire activity in these areas can also depend on rainfall in previous seasons and the consequent vegetative growth (Russell-Smith *et al*. 2007). In these areas, spatial and temporal shifts in precipitation patterns with climate change and the consequent changes in vegetation may be main drivers of changes in the timing of fire activity throughout the year.

Climate change research using GCM outputs in North America, Australia, the Mediterranean, and the boreal forest of Russia have shown an extension of conditions conducive to fire ignition and spread at both the start and end of the fire season (Wotton and Flannigan 1993; Goldammer and Price 1998; Stocks *et al*. 1998; Williams *et al*. 2001; Kochtubajda *et al*. 2006; Moriondo *et al*. 2006; Nitschke and Innes 2008), and such extensions of the fire season may have already begun. In a study of wildfire in the western USA, Westerling *et al*. (2006) found that fire season length had increased by over 2 months over the 1980s, using data from 1970 to 2003, and attribute the earlier start of the fire season to earlier snowmelt from higher spring and summer temperatures. In a case study in the province of Ontario, Canada, analysis of the date of initial fire activity showed progressively earlier starts to the fire season over the last two decades (R. McAlpine, pers. comm.). Like other studies around the globe on fire season length, Williams *et al*. (2001) suggested that fire season length may increase with future climate change; however, they also found that the length may decrease in some locations of Australia. Additionally, they suggested that the peak of the fire season in Australia may occur earlier or later in the year, depending on location.

There has been little research that examines the potential impacts of climate change on seasonal distributions of fire around the globe. Understanding these changes has great importance, particularly in those areas where fire suppression plays a critical role in protecting human life. If future fire regimes result in greater fire loads in the spring or fall seasons, fire management agencies will need to expand their current fire suppression capacity beyond the historical fire season limits. Such changes do not present technically insurmountable problems, but highlight the need to anticipate more subtle changes that arise from interaction of increased fire activity with fire management capacity.

Fire intensity

Fire intensity is a measure of energy output and is a function of the fuel burning and fire weather conditions. Given that changes in climate will affect the growth and distribution of vegetation as well as weather conditions, the net result on fire intensity is a challenge to predict. The importance of future projections of fire intensity lies in its relationship to fire behaviour, suppression effectiveness, emissions, fire effects (e.g. fire severity) and feedbacks to vegetation dynamics through soil conditions and via the life-history strategies of flora. In areas dominated with long-lived flora, such as trees, the effects of climate change on fire intensity are more likely to manifest themselves through changes in fire weather conditions rather than changes in fuel load. However in grassland, savanna or deserts dominated by short-lived or more episodic flora, changes in climate could promote rapid changes in fuel availability such that fire intensity could be significantly altered even with little change to fire weather conditions.

Relatively little work has been done to study future fire intensities, and those studies demonstrate the complexity arising from the interaction of changing fuel and weather conditions. Lenihan *et al*. (2008) used the dynamic vegetation model (DVM) MC1 and climate change data from the Hadley and Parallel Climate Model (PCM) GCMs to project changes in fire intensity across California. The Hadley data projected increases in precipitation that led to more biomass of both trees and grasses, which resulted in more fire and greater fire intensities. However, an increase in precipitation also reduced fire weather conditions in some years, and the relatively wet years led to a build-up of biomass, priming the system for higher fuel loads in relatively dry years that followed. In contrast, climate data from the PCM showed a widespread biomass decrease in response to projected decreases in annual precipitation, leading to an increased amount of drought-resistant grasses. This simulation experiment illustrates how the relationship between fire intensity and climate is non-linear and complex in the long term owing to the super-ordinate position of climate driving both vegetation and weather. Furthermore, the study underscores the variability in future fire projections generated by model-dependent predictions of future precipitation. Malanson and Westman (1991) demonstrated that changes in fuel load and vegetation composition associated with climate change led to increased fire intensity, which led to further changes in vegetation composition using a model of California shrublands. The relationships between fire intensity and life-history characteristics illustrate the potential for feedbacks between intensity and vegetation.

In the boreal forest, de Groot *et al*. (2003) showed that more severe burning conditions led to higher-intensity fires in all forest types in a study of the western Canadian boreal forest, using climate data from the Canadian GCM and the BORFIRE fire effects model of forest dynamics. In a comparison between 2080–2100 and 1975–90 conditions, de Groot *et al*. (2003) determined that increased fire intensity gave a small advantage to thicker-barked species but also led to an increase of deciduous species that resprout after fire. The latter generated a negative feedback to fire regime because a shift towards these deciduous species promotes a reduction in fire intensity, even under more severe fire weather conditions. Taking a simpler approach, Kafka *et al*. (2001) studied changes in fire intensity for boreal forests of Saskatchewan, Canada, using static fuel data and changing fire weather projected from the Canadian RCM. One would expect this simpler method to show parallel results to DVMs in near-future projections. Similarly to de Groot *et al*. (2003), Kafka *et al*. (2001) calculated an overall increase in fire intensity at $2 \times CO_2$ climate conditions with significant spatial variation due to the interaction and heterogeneity of fuel types and weather. There was little additional change detected under $3 \times CO_2$ conditions. In south-central British Columbia, Nitschke and Innes (2008) suggest that the fire regime may shift towards more crown fires (fires of higher intensity).

Alongside climate-mediated changes, future fire intensity will also be influenced by management decisions. Forest and fire management decisions can lead to the reduction or accumulation of fuel load, and thus can influence fire intensity (Shang *et al*. 2007). Fuels management is a contentious area of forest policy in many parts of the world where the wildland–urban interface continues to bring human development and fire in close proximity (Moritz and Stephens 2008). Fuels management accomplished through the alteration and reduction of burnable biomass is not intended to stop fires from burning through an area, but rather, to reduce the intensity of a fire such that fire suppression resources can be effective and deployed safely. However, fuels management is only an effective fire management strategy in small areas of high value; operational application of this strategy at the landscape scale would incur great economic and ecological costs (Finney 2007).

Fire severity

Very little research has been done on the effects of climate change on fire severity[1]. Under future climate scenarios of $2 \times CO_2$ (Amiro *et al*. 2009) and $3 \times CO_2$ (de Groot *et al*. 2003; Amiro *et al*. 2009) using the Canadian GCM (CGCM1), fire severity in boreal Canada was found to be greater than the $1 \times CO_2$ scenario. However, Amiro *et al*. (2009) found the increase in ground fuel consumed (0–18%) was small in comparison with the total increase in fuel consumption due to the increase in future area burned. Furthermore, future fire severity could additionally increase or decrease if there is a shift in the seasonal timing of area burned. Ground fuels are generally wettest early in the fire season and driest late in the fire season, leading to low fire severity in the spring and higher fire severity in the autumn (Russell-Smith *et al*. 2009). A general expansion in the fire season length is expected (Wotton and Flannigan 1993), but it is not known whether this would significantly affect the seasonal timing of the majority of area burned. Another factor that could substantially influence future fire severity is fuel load (Amiro *et al*. 2009). Climate change is likely to influence forest fuels through stand composition, growth rates, age-class structure, litterfall, and decomposition rates. Fire severity is strongly influenced by fuel load (de Groot *et al*. 2009), but the net impact of these many factors contributing to future fuel load is unknown.

Future directions

Modelling: impacts of future fire activity

Modelling provides systematic methods to project future fire activity in the context of climate change, and in some cases, to explore the subsequent effects of changes in fire on the biosphere and atmosphere. At regional and global scales, D(G)VMs and statistical models have been two dominant approaches used to examine future fire activity associated with climate change, whereas landscape fire succession, fire probability, and stand models are used at finer scales.

A DGVM is a bottom–up, or process-based, land biogeochemical model. The importance of fire as a global system process, and thus the necessity for its inclusion in DGVMs was highlighted by Fosberg *et al*. (1999). The seminal work by Bond *et al*. (2005) illustrated the strong role of fire in global biogeography by comparing DGVM output when the fire module is on with when it is turned off, showing dramatic reduction in the extent of forested systems as a function of fire. However, the complexity of fire is difficult to model in DGVMs, but has been included with varying success (Thonicke *et al*. 2001, 2005; Arora and Boer 2005; Crevoisier *et al*. 2007; Venevsky and Maksyutov 2007). For a fire module to be useful in understanding fire–climate changes, it must respond to climate parameters. Fire–climate relationships have been modeled rather simply using soil or litter moisture content (Thonicke *et al*. 2001), while recent advances, such as in the Canadian Terrestrial Ecosystem Model, have added mechanistically explicit representations of fire, namely biomass to burn, fire weather conditions, and an ignition source, as well as calculations for determining area burned, mortality and fire emissions (Arora and Boer 2005). The module embedded in the Lund–Potsdam–Jena (LPJ) DGVM, named SPITFIRE (Spread and Intensity of Fires and Emissions), explicitly uses climatic fire danger indices and lightning- and human-caused ignitions and more complex consideration of fire intensity and post-fire mortality.

The recent development of more meaningful fire modules within DGVMs illustrates that examination of the future of fire activity and fire effects at a global scale is not out of reach. At a regional scale, DVMs have been used to project future fire activity and its effects by using data from GCMs to drive the climate contribution to DVMs. Alternatively, a DGVM can be interactively coupled 'online' with GCMs such that the DGVM provides global biogeochemical feedbacks to the atmosphere, a climate–carbon cycle not included in the general land surface models of atmosphere–ocean general circulation models (AOGCMs) (Bonan *et al*. 2003; Friedlingstein and Cox 2006). Few global models that currently engage in this coupled complexity also include fire, yet this is the direction in which global systems modeling contributing to the International Panel on Climate Change (IPCC) needs to be, and is, headed (Running 2008). As combustion leads to the production of radiatively active gases, aerosols and their precursors, and trace gases including nitrous oxides (NO_x), CH_4, and CO_2, it is critical that we further our understanding of the effects and feedbacks of vegetation fires in the earth–atmosphere system. Models with soil–vegetation–fire–atmosphere feedbacks within a fully coupled GCM are a grail concept. In addition, the inclusion of human–fire relationships will be a tricky but necessary next step in model development (Running 2008). Human behaviour is extremely difficult to simulate owing to unexpected changes in policy and social norms. However, the strong effect of humans on fire, through ignition, fire management, and land-cover change, cannot be ignored. Additional factors to consider for modelling future fire activity are other natural disturbances such as insects, forest diseases, droughts, storms, and landslides. These disturbances have the potential to increase in the future, and research is needed to predict how they will respond to the direct and indirect effects of climate change and their interactions (see Swetnam and Betancourt 1998; Volney and Fleming 2000; Galik and Jackson 2009).

More commonly, D(G)VMs are run offline, driven by climate data from GCMs and as such, climate does not respond to the vegetation model. Numerous studies have partnered D(G)VMs with climate change data in this fashion to quantify changes in wildfire over regional or global extents (Cramer *et al*. 2001; Bachelet *et al*. 2005; Scholze *et al*. 2006; Lenihan *et al*. 2008). Though GCMs are in agreement that temperatures will rise globally, there is still heterogeneity among models in expected temperature changes, and precipitation fields vary widely among climate models (Meehl *et al*. 2007). As fire occurs through the interplay of temperature and precipitation, fire projections from dynamic climate change experiments using GCM or RCM data can vary greatly among climate models and among vegetation models (Cramer *et al*. 2001). Model comparisons, such as those hosted by The Program for Climate Model Diagnosis and Intercomparison, provide necessary perspective for understanding

[1]The term 'fire severity' is used in different ways in the published literature. Here, it is defined as a component of the fire regime: indicating depth of burn or fuel consumption of the ground layer.

uncertainty and trends associated with GCMs (Meehl *et al.* 2007). Despite model uncertainty, it is interesting to note that the interplay of temperature and precipitation are currently predicted to result in increases in fire frequency over some regions of the world and decreases in others (Scholze *et al.* 2006).

Global and regional projections of fire activity in response to climate change have also been developed using statistical distribution models, similar to niche models or climate envelopes used to project shifts in biogeographies with climate change. With this approach, the statistical relationship between historical fire activity and climate is developed, in essence a pyrogeography, and the parameters from the models are then used with climate data from GCMs to project the future of fire. Examples of these methods have been used to project future fire activity globally (Krawchuk *et al.* 2009*a*), in the boreal forest of Canada and the United States (Flannigan *et al.* 2005; Balshi *et al.* 2008), and in the western United States (Westerling and Bryant 2008). These statistical models project the emergent properties of climate change on fire based on historical data patterns, rather than modeling the processes responsible for fire explicitly, as is done using the DGVM. The cost is a loss of mechanistic understanding; however, benefits include the fact that projections are not conditional on the correct definition and calibration of parameters for multiple, interacting lower-level process equations as required in DGVMs. Of course, GCM model inter-comparisons are still necessary. At a global scale, the comparison and consilience of statistical, DGVM and fully coupled AOGCM approaches will be essential in understanding global fire activity and climate change.

Including climate change in finer-scaled stand or landscape vegetation–succession models (Mouillot *et al.* 2002; He *et al.* 2005; Cary *et al.* 2006, 2009; Keane *et al.* 2008) can also contribute to global fire science. It is at these scales where fire effects, behaviour, and vegetation dynamics not currently computationally feasible at global scales can be best examined. These landscape and stand models are particularly useful for determining the relative influence and sensitivity of wildland fire to key factors such as vegetation, topography, weather, and climate change. Additionally, these models are useful to explore the interaction of management decisions with climate change on fire activity. The synthesis of multiple studies from disparate parts of the world can help to understand the future of the global fire cycle.

Fire management

Wildland fire management problems are increasing globally for numerous reasons. There is increasing use of fire for conversion of vegetation during land-use change, particularly in fire-sensitive tropical biomes. Demographic changes in some regions are resulting in rural exodus as traditional, sustainable, land-use systems are abandoned, causing changing vegetation and fuel conditions (Mouillot and Field 2005). In some countries, poverty, exurban migration and land-tenure conflicts result in increased human-caused fires (Henderson *et al.* 2005; Xanthopoulos *et al.* 2006; Pyne 2008). In other regions, the wildland–urban interface continues to expand (Cottrell 2005; FAO 2007; Theobald and Romme 2007; Zhang *et al.* 2008). Common global problems include increasing fire suppression costs, and increased hazardous emissions (often with transboundary transport) causing greater negative human health impacts (Goldammer *et al.* 2009). Fire management agencies worldwide also recognize the consequences of, and the contribution of fire to, climate change. Impacts of climate change on the fire environment are generally seen with the trend of increasing area burned, fire occurrence, fire intensity, fire severity, and longer fire seasons (Table 1).

There are many parts of the world where wildfires are left to burn freely, including large areas of the northern boreal forest in Canada and Russia, and areas of northern grasslands in northern Australia. However, in the majority of forested landscapes, some form of fire management is practiced. In forested areas with high population densities and other values, fire management most often means attempted fire exclusion: that is, all fires are actively suppressed to try to limit their extent and values impacted. This focus on fire exclusion has in some areas (e.g. areas of the western USA) led to increased fuel loads (and fuel continuity) and greatly increased fire potential.

As has been discussed in the present review, climate change has the potential to lead to increases in fire activity in many boreal and temperate forests around the world. Here, largely owing to the relative wealth of literature from North America and the North American bias of the authors, we use examples from the USA and Canada to discuss fire management concerns in the near future. The obvious question that arises is: can forest fire management agencies adapt and mitigate the impacts of this potential increase in fire activity through increasing resource capacity? It was suggested by Stocks (1993) that under climate change, a disproportionate number of fires may escape initial attack, resulting in very significant increases in area burned. The reasoning behind this hypothesis was that there tends to be a very narrow range in the transition between the overall suppression system's success or failure; that is, typically (e.g. 90% of the time or more), a fire management agency functions at optimal performance, suppressing fires quickly and at small sizes, until the active fire load[2] increases to the point of maximum fire suppression capacity, after which delays in initial attack can lead to large numbers of escape fires. Detailed simulation of the initial attack system of Ontario's fire management agency, which actively manages fire across ~50 Mha of boreal forest in Canada, showed that to move the escape fire threshold down from current levels, very significant investment in resources would be required (McAlpine and Hirsch 1998); that is, incremental increases in fire suppression resource lead to diminishing gains in initial attack success. A further study using Ontario's initial attack simulation system with future climate change scenarios of fire weather and occurrence showed that current resource levels would have to more than double to meet even a relatively small increase (15%) in fire load (Wotton and Stocks 2006). An agency's fire load threshold is not the only physical limit that might play a role in future success and failure of fire management objectives under a changed climate. Direct fire suppression methods, including high-volume airtanker drops, become relatively ineffective once fireline intensities are on the order of 4000 to 10 000 kW m^{-1}, intensities that constitute the relatively

[2]The number of fires and difficulty in controlling those fires is generally indicated here by the term 'fire load'.

low end of the crown fire regime. Thus, if fire intensities are to increase as suggested earlier in the present paper, one can expect the number of situations when direct fire suppression activity is ineffective to increase as well. Adaptation to new fire climates may require fire agencies and the public to re-examine their current tolerance of fire on the landscape, or think beyond fire management practices of the 20th century to mitigate unwanted fire. Options such as treating fuels in the immediate vicinity of values at risk may be one of the few viable solutions available (e.g. Cary *et al*. 2009), along with strategically placed landscape fuel treatments (Finney 2007).

In the vast areas of the globe dominated by human-caused fire, one might think increased fire prevention campaigns and enforcement of restricted fire zones might help reduce the number of starts during high fire-potential periods. However, areas with well-established fire prevention programs, such as southern California, still tend to have a significant human-caused fire load, though this may be due in part to the rise of arson in recent years. Human-caused fires tend to cluster around areas where human activity and fuels are coincident. This has both advantages and disadvantages for fire management agencies. Advantages include quick detection and easy access to fires in areas with significant human activity. Disadvantages include high densities of values that need protecting in such populated areas. It is difficult to predict what changes in societal values or demographics might occur over the next century that will have a direct impact on the number of human ignition sources on the landscape. What does seem clear is that in areas where fuel is available, environmental conditions (i.e. fuel moisture) will be more conducive to ignition in the future. Without major changes in patterns of human activity or fuels, the number of fires occurring from human causes will likely increase and thus the presence of fire in high-value areas, and the consequent pressure on fire management agencies to deal with this fire, will likely increase. Through most of the 20th century in most of the world, 'fire management' organizations tended to be fire suppression organizations, focussed on fire exclusion. Today, there is a recognition of the need to balance fire suppression to protect values (e.g. in the wildland–urban interface, or in high-value timber production areas) with the need to let fire in wilderness areas burn. Increased fire activity due to climate change, and increased awareness of carbon emission from wildfire as well as potential newly available sources of carbon emissions, such as boreal peatlands (Flannigan *et al*. 2009), are added pressures that will make achieving a balance between value protection and the ecological needs for fire even more difficult for fire management agencies.

There is a lack of integrated fire management capacity in many countries around the world. This includes integration of technical and human resources, which can reduce fire management capability at scales ranging from local to global. The international fire community recognizes that greater international cooperation is required to overcome lack of integration and reduced fire management capacity in the face of increasing global fire activity. A Strategy to Enhance International Cooperation in Fire Management includes (i) development of international standards and systems for fire early warning, monitoring, impact assessment and reporting; (ii) training and technology transfer; (iii) policy, planning, and institutional support; and (iv) research (FAO 2006).

Summary

A great deal of research has been completed on wildland fire and we are beginning to understand the relationships between various aspects of fire activity and the key factors such as weather–climate, fuels, and people, along with their interactions; however, there is a definite lack of wildland fire and climate change publications for many parts of the world that needs to be addressed. These factors regulating wildfire are dynamic and will continue to change as the climate, fuels, and people respond to global change and other influences. Overall, we expect that fire activity will continue to increase owing to climate change. It appears that area burned and fire occurrence are generally increasing, but there will be regions with no change and regions with decreases. The length of the fire season in the temperate and boreal regions of the world appears to be increasing already and should continue to lengthen in the future. Fire intensity and severity are more difficult to summarize and this is an area in need of further research. There could be surprises in the future, perhaps even the near future, with respect to fire activity and this is due to our limited understanding of the interactions between weather–climate, fuels, and people.

Earlier we raised the question about whether global wildland fire activity could be moving towards a critical threshold or breaking point; we cannot answer that question at this time because of lack of data and understanding. However, it is possible that rapid and unexpected changes in regional regimes or the global fire regime may be on the horizon. As a result of climate change, we are in essence conducting a global experiment such that future wildland fire activity is highly uncertain.

The role of people in global fire regimes needs much more work as policy, practices, and behaviour vary across the world and with time. Most global fire is directly attributed to people and most of the fire occurs in grasslands and savannas, primarily in Africa, Australia, South America and South Asia; we have very limited data on fires in these regions. The more physical aspects of wildland fire have received greater attention by the research community but there are still areas that need further work including global studies that dynamically model weather, vegetation, people, fire, and other disturbances. Lastly, we require accurate global datasets of fire activity. The advent of satellite sensors appropriate to monitor wildland fire has been a significant advance in terms of area burned but even those data provide a wide range of estimates, and we still do not have an accurate estimate of global fire occurrence. However, the growing recognition of the importance of fire in global systems (Bowman *et al*. 2009) bodes well for transdisciplinary understanding of the inter-relationship of climate change and wildland fire.

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