Global change and fire regimes in Australia

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Abstract

Global change can be defined strictly in terms of changes in atmospheric composition, climate and land use (Walker and Steffen 1996), although broader definitions also include human population, economy and urbanisation (Steffen et al. 2004). In Australia, global change significantly affects the drivers of fire activity and there is potential for considerable changes in fire regimes. It is widely accepted that carbon dioxide (CO_2) concentration in the atmosphere is steadily increasing (see Steele et al. 2007), as is nitrous oxide (Forster et al. 2007). Atmospheric methane concentration has also risen significantly, but is now relatively constant (Beer et al. 2006). Given the increase in these greenhouse gases, an increase in the energy trapped by the atmosphere is expected, resulting in atmospheric warming (Arrhenius 1896; IPCC 2007). Therefore, Australia's climate is changing. Average temperatures are expected to increase by between 0.6 and 4°C, depending on emission scenario, timeframe and locality (CSIRO and Australian Bureau of Meteorology 2007) (Figure 7.1). Patterns of precipitation are projected to shift by the end of this century, with higher precipitation in the continent's north and east and declines in the south and west - a pattern generally mimicked by evaporation (Lim and Roderick 2009) (Figure 7.2). Average relative humidity could decline by up to 4% in central and eastern Australia by 2070, while average wind speed may increase by 10% in similar areas (see CSIRO and Australian Bureau of Meteorology 2007). The frequency of extreme frontal events may double or more by the end of this century (Hasson et al. 2009), yet outcomes for circulation patterns associated with El Niño and the Southern Oscillation (ENSO) (Philander 1990) are uncertain (Collins et al. 2010). Importantly, uncertainty arising from choice of emission scenarios and climate sensitivity, and from differences among models, is common (CSIRO and Australian Bureau of Meteorology 2007; Lim and Roderick 2009).

Keywords

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Abstract

Bushfire regimes in future Australian landscapes will be determined by complex interactions arising from increasing atmospheric CO_2, global warming, the spread of invasive fuel species and increasing human populations. These interactions directly and indirectly influence the key factors that determine fire regimes, namely biomass growth, fuel availability, fire weather and ignitions. Higher temperature and wind speed, lower humidity and variable effects on moisture budgets are likely to increase fire danger generally. Fuel loads will most likely reflect the balance of decreased productivity (climate), increased productivity (CO_2) and decreased decomposition (C:N ratio). Shifting assemblages of plant species ('communities'), including spread of invasive species, are also important but likely to be difficult to predict. Ignitions from lightning and humans are expected to increase overall. Insights into possible effects of these changes on fire regimes are available from palaeo-records and simulation modelling, indicating climate exerts a strong control on fire activity. Significant shifts in fire regimes are possible, although definitive predictions remain elusive given global change effects on fire activity may be synergistic or antagonistic and because the relative magnitude of different effects is unclear. The implications of future fire regimes on biodiversity will depend also on direct effects of global change on species.

Introduction

Global change can be defined strictly in terms of changes in atmospheric composition, climate and land use (Walker and Steffen 1996), although broader definitions also include human population, economy and urbanisation (Steffen *et al.* 2004). In Australia, global change significantly affects drivers of fire activity and there is potential for considerable changes in fire regimes.

It is widely accepted that carbon dioxide (CO_2) concentration in the atmosphere is steadily increasing (see Steele *et al.* 2007), as is nitrous oxide (Forster *et al.* 2007). Atmospheric methane concentration has also risen significantly but is now relatively constant (Beer *et al.* 2006). Given the increase in these greenhouse gases, an increase in the energy trapped by the atmosphere is expected, resulting in atmospheric warming (Arrhenius 1896; IPCC 2007).

Therefore, Australia's climate is changing. Average temperatures are expected to increase by between 0.6 and $4^{o}C$ depending on emission scenario, timeframe and locality (CSIRO and Australian Bureau of Meteorology 2007) (Figure 1). Patterns of precipitation are projected to shift by the end of this century, with higher precipitation in the continent's north and east and declines in the south and west, a pattern generally mimicked by evaporation (Lim and Roderick 2009) (Figure 2). Average relative humidity could decline by up to 4 per cent in central and eastern Australia by 2070, while average wind speed may increase by 10 per cent in similar areas (see CSIRO and Australian Bureau of Meteorology 2007). The frequency of extreme frontal events may double or more by the end of this century (Hasson *et al.* 2009), yet outcomes for circulation patterns associated with El Niño and the Southern Oscillation (ENSO) (Philander 1990) are uncertain (Collins *et al.* 2010). Importantly, uncertainty arising from choice of emission scenarios and climate sensitivity, and differences among models is common (CSIRO and Australian Bureau of Meteorology 2007, Lim and Roderick 2009).

Wider aspects of global change are considerable and will continue to feature prominently in Australia's future. Australia's population may increase from around 21 million in 2007 to 28.5

million in 2047 (Australian Government, The Treasury 2007). Changes in land-use practices (Walker and Steffen 1996) have been a prominent feature of Australia's past (Barson *et al*. 2000) and will likely continue, facilitating ongoing changes in vegetation and spread of invasive species.

These changes have considerable potential to alter patterns of fire occurrence, resulting in significant economic impacts in agricultural, tourism and health sectors (Garnaut 2008), and important effects, via biotic responses, on Australian biodioversity (Bradstock *et al.* 2002). The objective of this chapter is to present insights into selected global change effects on key drivers of fire activity and to explore how these might interact to influence future fire regimes. Insights from the inter-relationship between climate and fire in the palaeoecological record is briefly addressed but dealt with in greater detail in Mooney *et al.* (this volume).
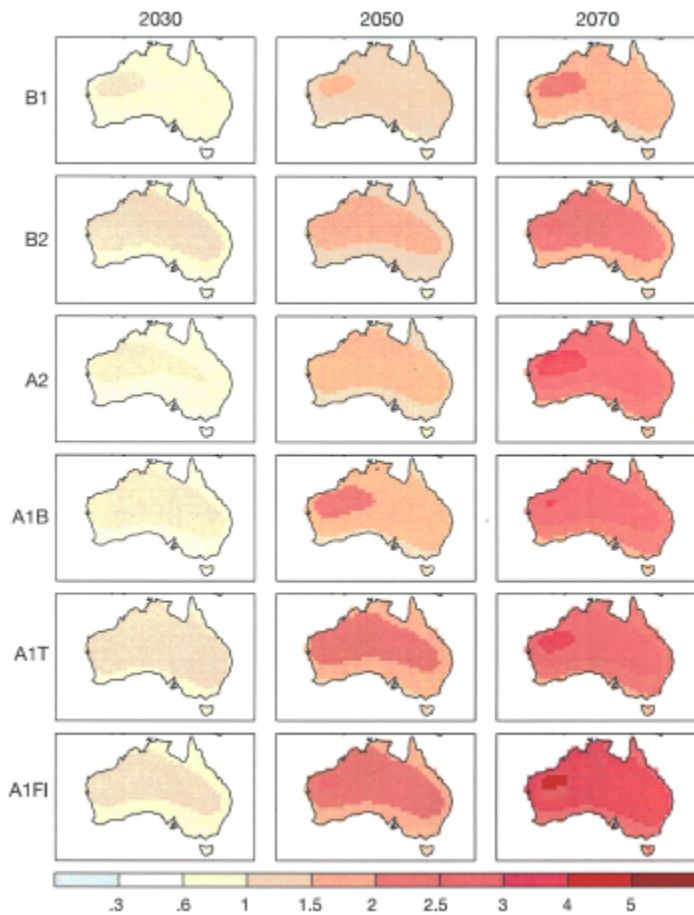
Figure 1. Best estimate (50th percentiles) of projected change of mean annual temperature (°C) for 2030 (left column), 2050 (middle) and 2070 (right). Results for six emission scenarios (B1, B2, A2, A1B, A1T, A1FI) are given. (Source: CSIRO and Australian Bureau of Meteorology (2007): http://climatechangeinaustralia.com.au).
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Figure 2. Projected average changes in precipitation (P), evaporation (E) and their difference (P–E) from 1970–1999 to 2070–2099 averaged across 39 model runs from 20 Global Circulation Models, assuming a mid-range emissions scenario (A1B) for a future climate (Source: Lim and Roderick 2009). Reproduced by permission of ANU E Press.

Global change effects on drivers of fire occurrence and behaviour
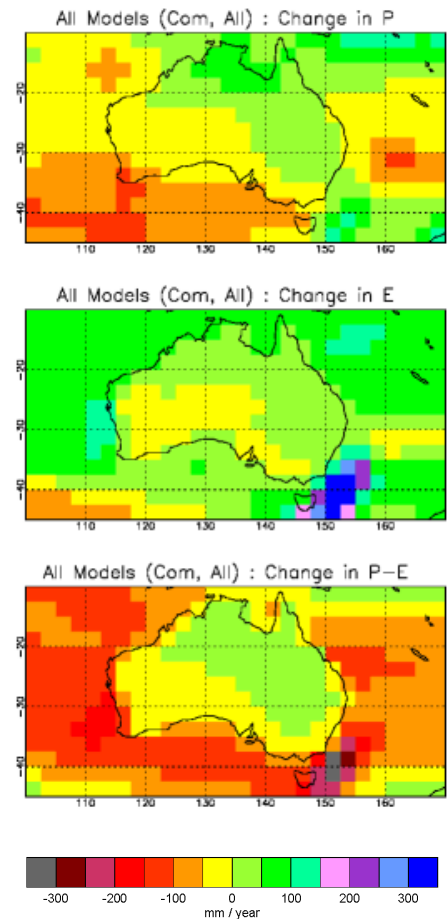
The key drivers of variation in fire activity are variation in fuel, weather and ignition rates (Flannigan *et al.* 2009; Krawchuck *et al.* 2009*a*; Bradstock 2010). These factors determine the timing and nature of the fires that characterise fire regimes (*sensu* Gill 1975). The extent that global change will affect fire regimes depends on complex interactions across these key drivers (Figure 3) and on the extent to which individual drivers are limiting factors for fire occurrence in any particular biome (Bradstock 2010).
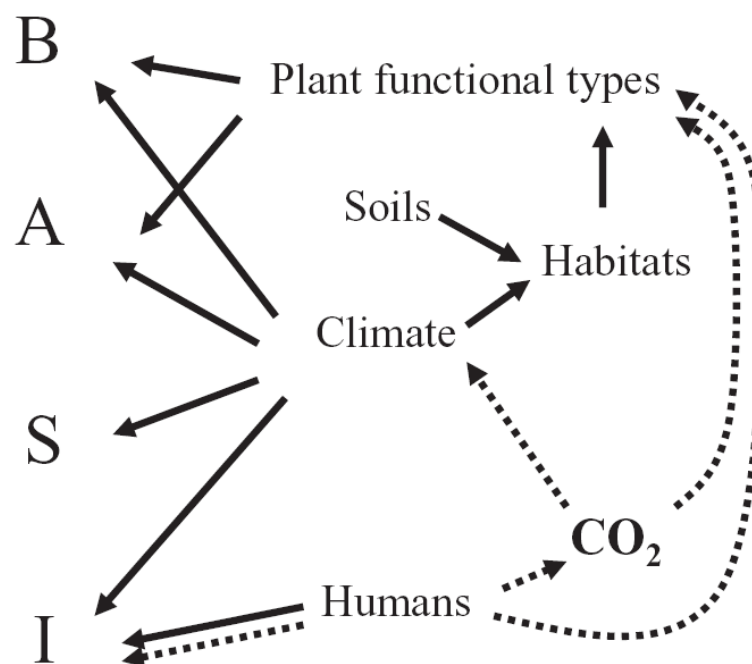
Figure 3. Influences of biogeographic factors (climate, soils, habitats, plant functional types) on fire regimes via four 'switches' (Biomass growth – B; Availability of fuel for burning – A; Ambient fire weather – S; and Ignitions – I). Potential effects of changing climate, human activity and atmospheric CO_2 are indicated by dashed lines. (Source: Bradstock 2010).

Weather (A, S)

Ambient and antecedent weather influences availability of fuel and aspects of fire behaviour including rate of fire spread (Catchpole 2002; Gould *et al*. 2007) and fireline intensity (Byram 1959). Cary (2002) reviewed the potential effects of future climate change on fire danger, an indicator of

ignition likelihood, rate of spread, intensity and difficulty of suppression (McArthur 1967), and fire regimes (Gill 1975) in Australia. Early projections suggested: (i) a 10 to 20 per cent increase in annually summed Forest Fire Danger Index (ΣFFDI) in south-eastern Australia (Beer *et al*. 1988); and (ii) a general increase in ΣFFDI, commonly greater than 10 per cent, across Australia, with some small areas where ΣFFDI was expected to decrease (Beer and Williams 1995). More recently, various analyses have shown a reduction in days with lower fire danger rating, and an increase in days characterised by higher fire danger might be expected (Williams *et al*. 2001; Hennessy *et al*. 2005; Lucas *et al*. 2007). Data from most weather stations in south-eastern Australia show a significant non-linear increase in ΣFFDI over the period 1970–2007, with the largest increases observed for inland areas (Lucas *et al*. 2007). Similar patterns have been observed for weather stations around Australia (Williams *et al*. 2009). Longer term trends (1940–2007) exhibit weaker or non-existent trends in ΣFFDI (Lucas *et al*. 2007) (Figure 4).

Definitive data on temporal trends in fire activity spanning multiple decades are not readily available in Australia. Elsewhere, fire activity increased markedly in western forests of the United States around the mid-1980s, accompanied by a transition to longer fire seasons, drier vegetation and warmer spring weather (Westerling *et al*. 2006). Similarly, on the Spanish eastern-Iberian Peninsula, higher temperatures and drier summers over the period 1950–2000 coincided with an increase in the number of fires over the last three decades of the 20th century, although area burned showed no clear trend (Pausus 2004). The extent that these patterns have resulted from natural climate variation or socioeconomic dynamics, compared with anthropogenic global warming, continues to be debated. However, given a strong consensus among global climate models for warming under future scenarios (Meehl *et al*. 2007), rising temperatures may provide an important catalyst for increased fire activity in many parts of Australia and around the world (Flannigan *et al*. 2009; Krawchuk *et al*. 2009*a*).
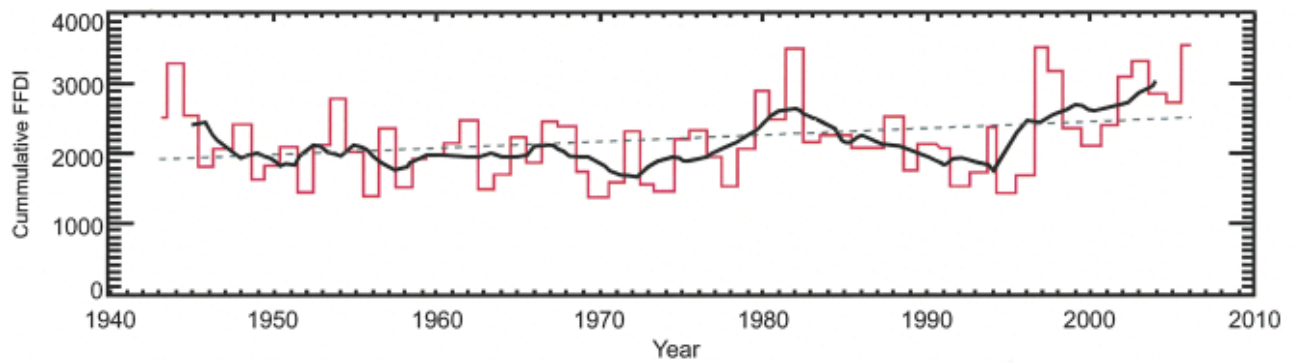
Figure 4. Long time-series of cumulative FFDI (ΣFFDI) at Melbourne airport. The five-year running mean is represented by the smooth black line. The dashed grey line is the linear trend (Source: Williams *et al*. 2009. See Esplin *et al*. 2003 and Lucas *et al*. 2007 for similar analyses). Reproduced by permission of the Department of Climate Change and Energy Efficiency.

Cary and Banks (2000) and Cary (2002) provided a simulation methodology for evaluating projected impacts of global warming on fire regimes. The technique incorporated climate change effects on fire behaviour, but excluded potential impacts on fuel dynamics and ignition rates. Undertaken in the Australian Capital Territory region, the analysis suggested that the direct effects of a 3.4°C temperature increase, with other meteorological variables scaled appropriately, would be to more than double the frequency of fire, increase average fireline intensity by around 20 per cent, increase area burned in autumn and reduce area burned in spring. Similarly, a systematic comparison of the effect of warmer climates across a suite of landscape fire models from around the world (Cary *et al*. 2006) (Figure 5) and recent Australian case studies (Bradstock *et al*. 2008; King *et al*. in press) confirmed that an increase in area burned might generally be expected, assuming direct effects on fire weather only.

a)

FIRESCAPE - south-east Australia

b)

LAMOS - Corsica

c)

LANDSUM - Northern Rocky Mountains

d)

SEM-LAND - West -central Alberta

e)

EMBYR - Yellowstone National Park
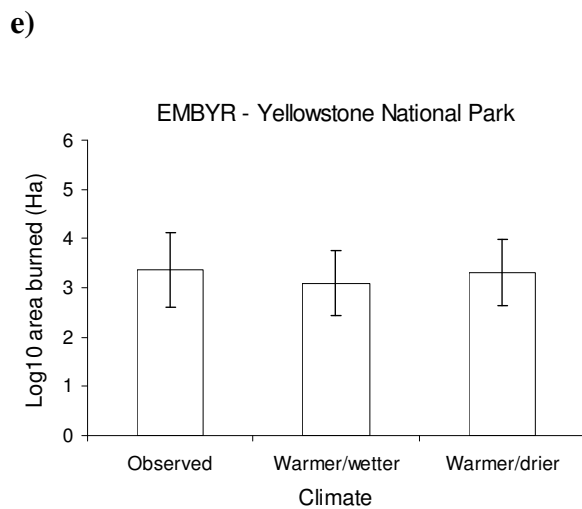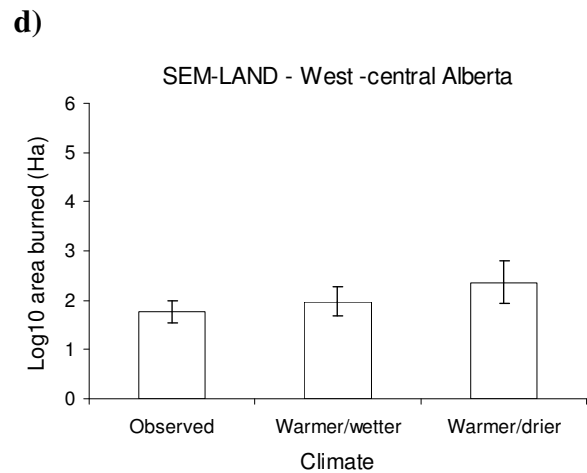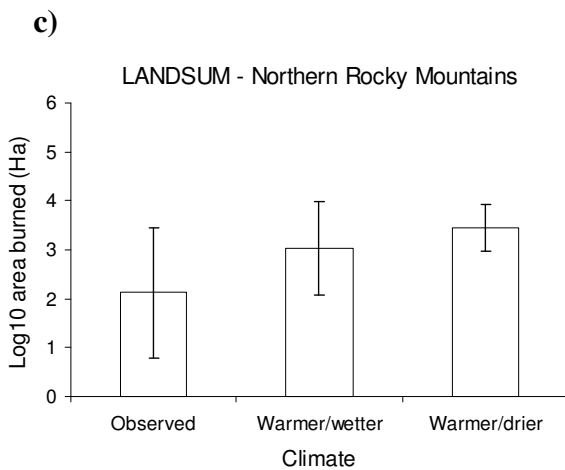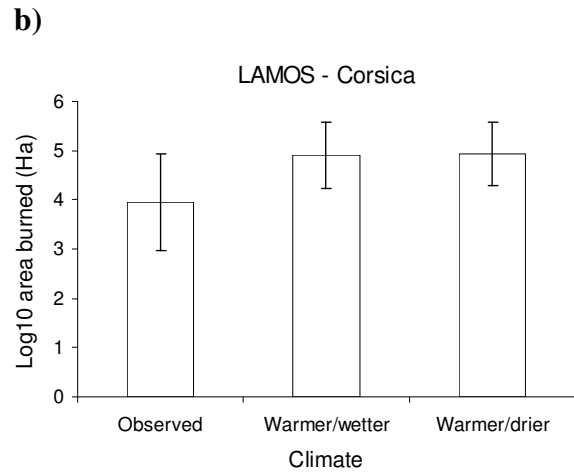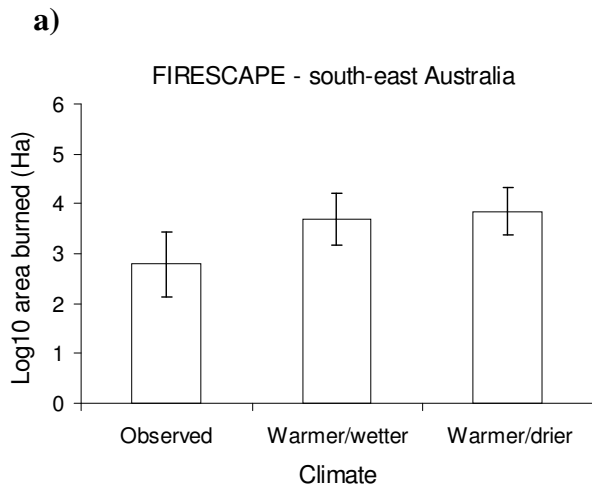
Figure 5. Area burned under three climate scenarios in a comparison of landscape-fire models (see Cary *et al.* 2006) (a) FIRESCAPE – south-eastern Australia; (b) LAMOS(HS) – Corsica; (c) LANDSUM – northern Rocky Mountains; (d) SEM-LAND – west-central Alberta; (e) EMBYR - Yellowstone National Park. Warmer climates assume a 3.6°C temperature increase over observed climate. The wetter climate equates to a 20 per cent increase in precipitation and the drier climate assumes a 20 per cent precipitation decline. Differences in area burned are expected between locations because of variation in climate/fuel/ignition dynamics. Four of the location/model combinations (a–d) show increased area burned for warmer climates (drier, wetter, or both) while one (e) shows no significant trend. (Source: Williams *et al.* 2009). Reproduced by permission of the Department of Climate Change and Energy Efficiency.

Fuel (B)

Gould *et al*. (2007) classified fuel into six vertical layers ranging from fuel in the soil to that in the overstorey or canopy. Characteristics of each fuel category may influence fire behaviour, although key considerations are the dominant fuel type and amount (Catchpole 2002).

Fires predominantly burn litter, grass and shrubby biomass (Catchpole 2002), although other fuel components, including canopy leaves and bark, become increasingly important in higher intensity fires (Gould *et al*. 2007). Fuel dynamics are governed by rates of production and decomposition (Olson 1963; Walker 1981) and there is considerable potential for these processes to be altered in response to elevated levels of atmospheric CO_2, a warmer climate, and shifts in the distribution of vegetation types or their major components.

Changes in fuel accumulation

Plant growth rates influence grass and litter production. Plant productivity is partially controlled by the dynamics of temperature and moisture regimes (Krawchuk *et al*. 2009*a*), with enhanced productivity expected under cooler, moister regimes and decreased productivity likely under drier conditions (Pausas and Bradstock 2007; Lenihan *et al*. 2008). Thus, higher temperatures and decreased soil moisture, in isolation, will likely result in lower rates of fuel production and lower levels of accumulation.

However, given that carbon is the major building component for green plants, elevated atmospheric CO_2 has potential to increase plant growth and fuel production, although Norby *et al*. (2005) identified several factors that could limit this effect. Higher atmospheric CO_2 concentration has been shown in Free-Air CO_2 Enrichment (FACE) experiments to enhance productivity in fast-growing, early-successional stands by as much as 23 per cent in three deciduous forests (USA, Italy) and a *Pinus* forest (USA) (Norby *et al*. 2005). The effect is not universally observed, particularly for mature forests (Caspersen *et al*. 2000; Körner *et al*. 2005) and variation in allocation among species would result in differences in litter deposition and accumulation rates. A FACE experiment in mixed

Pinus taeda (loblolly pine) – hardwood forests (USA) resulted in significantly increased litterfall, due to increased litter and bark production in loblolly pine but not other species (Finzi *et al*. 2001). Further, inter-community variation in competitive ability, in relation to otherwise limiting resources, generally reduces the CO_2 fertilisation effect overall (Wang 2007). Elevated CO_2 can also enhance productivity, and potentially fuel loads, in grasslands. For example, doubling atmospheric CO_2 concentration from 360 to 720 umol/mol resulted in a 44 per cent increase of above-ground biomass in shortgrass steppe (USA), being largely attributable to one species' ability to establish seedlings under the changed conditions (Morgan *et al*. 2004).

Rates of litter decomposition depend on climate, litter composition and the composition and abundance of microbial and macro-invertebrate decomposer communities (Brennan *et al*. 2009). Limiting factors for decomposition vary, although moisture content exerts considerable control over litter decomposition compared with temperature, particularly in drier environments (Murphy *et al*. 1998; Wood 1970). Future shifts in moisture balance (Lim and Roderick 2009) are therefore likely to be critical in many ecosystems, although moisture regimes may be less important for decomposition rates of coarse wood (Brown *et al*. 1996). Further, the ratio of carbon to nitrogen (C:N) in plants, which is predicted to increase with higher atmospheric CO_2 concentration (Kanowski 2001), will likely result in lower decomposition rates of plant litter (Taylor *et al*. 1989) and decreased palatability of leaves for herbivores (Gleadow *et al*. 1998; Hovenden and Williams 2010). The effect on decomposition of coarse wood is less clear (Brown *et al*. 1996). Thus, decomposition rates of litter and grass are likely to decline (Kanowski 2001; Stokes *et al*. 2005), perhaps resulting in fuel beds with greater amounts of fine rather than coarse components. There will be complex future interactions between climate, CO_2, litter quality, composition of decomposer assemblages and fire frequency that are yet to be fully understood. However, slower rates of decomposition of plant material in the future may be associated with more frequent fire (Brennan *et al*. 2009).

Few studies have directly addressed the combined effects of altered productivity and decomposition on amount of accumulated fuel. Williams *et al*. (2009), using a climate gradient

representing decreasing rainfall and increasing potential evapo-transpiration along a Karri (*E. diversicolor*) - Wandoo (*E. wandoo*) transect, argue that a 20 per cent reduction in annual rainfall would result in a significantly greater reduction in litter load. By comparison, Lenihan *et al.* (2008), studying simulated ecosystems in California, suggest that a decline in productivity resulting from future drier climates may be compensated by lower decomposition. Our knowledge on likely future fuel dynamics and resultant effects on continuity of fuel across landscapes remains highly uncertain and further research aimed at unravelling the complexities involved is critical.

Changes in vegetation composition

Changes in climate and other aspects of global change will potentially cause modifications of species distributions and vegetation composition, significantly affecting fuel dynamics. Plant species are distributed across landscapes according to various environmental gradients, and in response to competition and disturbance regimes. For example, Whittaker (1965) developed the continuum concept demonstrating that species occupied many different and overlapping parts of an elevation gradient representing a proxy for variation in the temperature and moisture regimes that have a more direct effect. Each species occupies a particular environmental niche which is defined by the species' intrinsic responses to the environment, competition from other species and disturbance regimes (Austin 2002).

Species with overlapping distributions do not necessarily form discrete communities (see Austin 2002) and individual species, even those within an apparent 'community', may respond differently to future combinations of environmental stresses in a changing world. For example, Jarrad *et al.* (2008) examined the effects of experimental warming of air and soil on subalpine heathland plants in Victoria. The temperature increase of 0.8–1.4°C above ambient demonstrated that 'species respond individualistically to experimental warming'. Thus, forecasting changes in species assemblages is extremely difficult. Some species may migrate faster and further than others, while some may have no immediate habitat in which to establish and thus perish locally. Different dispersal distances may affect migration rate and thus new species assemblages may manifest at any

one place (see Austin 2002). Pollen transfer may enable wider dispersal of genes and non-equilibrium conditions may have important effects. Alternatively, if 'communities' are considered as being defined by particular dominant species, or physiognomic types, then synchrony in response may be more likely.

Despite this complexity, some general predictions are possible from insights into species' ecophysiology. Grasses, for example, can be split according to variation in their photosynthetic pathways. C3 grasses (e.g. *Poa*) are generally limited to temperate climates because photorespiration, which is expensive in terms of energy requirements, is limited by lower temperatures (Osborne 2008). C4 grasses (e.g. most savanna grasses, Lloyd *et al.* 2008) dominate in tropical and sub-tropical regions because their 'carbon-concentrating mechanisms' confer photosynthetic efficiency in warmer climates (Osborne 2008). Furthermore, elevated CO_2 enhances photosynthesis in C3 grasses more than in C4 species (Tubiello *et al.* 2007), although distribution of precipitation by growing season is critically important (Murphy and Bowman 2007). Redistribution of key grass types, with subsequent impacts on fuel dynamics, will depend on the relative advantages conferred to C4 grasses by higher temperatures and to C3 grasses by elevated atmospheric CO_2.

Similar potential for change exists for communities of woody species (Williams *et al.* 2009). Elevated levels of CO_2 can enhance growth of woody plants (Norby *et al.* 2005; Hovenden and Williams 2010) with differential allocation of carbon to plant parts then becoming an important consideration in understanding outcomes (McCarthy *et al.* 2006). Morgan *et al.* (2007) demonstrated significantly enhanced growth of a shrub in native shortgrass steppe (USA) and suggested that rising CO_2 levels may have contributed to shrub encroachments across grasslands in the last 100–200 years. With increasing shrub encroachment, pastoralists may react by increasing the imposed fire frequency to favour grasses and maximize grazing potential.

Finally, invasive grasses, which are often more flammable under a broader range of conditions than the native vegetation invaded, are an important consideration for fuel dynamics. Invasive grasses can increase fire frequency and area burned, providing greater opportunity for regeneration

and spread of the grass species, and thus initiating a positively reinforcing grass/fire cycle (D'Antonio and Vitousek 1992). Important examples in Australia include gamba grass (*Andropogon gayensis*) in tropical savannas (Rossiter *et al*. 2003) and buffel grass (*Cenchrus ciliatus*) in arid Australia (Clarke *et al*. 2005).

Ignition (I)

Broad-scale fire activity is strongly shaped by direct and indirect human ignitions and those derived from lightning (Krawchuck *et al*. 2009*a*). The majority of fires in Australia appear deliberately or accidentally ignited (Willis 2005; Russell-Smith *et al*. 2007), particularly near areas of high population density (Bradstock 2010). Nevertheless, lightning ignitions can result in considerable area being burned (McLeod 2003; Esplin *et al*. 2003). Future trends in ignitions will reflect changes in the ease of ignition of anthropogenic and lightning fires, or changes to ignition rates, or both.

Lightning trends

Lightning rates are sensitive to temperature (Williams *et al*. 2005), among other meteorological parameters. Pioneering exploration of global warming effects on global lightning distribution suggested a 5–6 per cent increase in global lightning activity for every 1°C increase in global temperature (Price and Rind 1994). Modelled cloud-to-ground lightning exhibited a greater sensitivity to warming with a 72 per cent increase in activity over continental areas arising from a 4.2^{o}C temperature increase in a General Circulation Model (GCM) experiment (Goldammer and Price 1998). Increases are expected to be greater in the tropics compared with higher latitudes. Empirical studies evaluating the relationship between temperature and lightning activity are rare, particularly in Australia where data are limited (Kuleshov *et al*. 2002). Lightning rates might also be indirectly affected by global warming. For example, Lutz *et al*. (2009) forecast an increase in lightning strike rates (not rates of lighting fire initiation) for the period 2020–2049 in Yosemite National Park, USA, because of an expected reduction in snow pack.

Lightning ignitions may also increase because fires may ignite more easily in the future. For example, an increased number of lightning-ignited fires are projected for global warming scenarios in central-eastern Alberta (Krawchuk *et al*. 2009*b*), independent of changes in lightning activity. Similarly, modelled future increases in area burned in the Australian Capital Territory region (Cary 2002) and in three landscapes in the Sydney region (Bradstock *et al*. 2008) resulted partly from a greater success of fire initiation, without changing rates of either lightning or anthropogenic ignition.

Trends in human ignitions

Rates of ignition are correlated with population density (Keeley and Fotheringham 2001) and ignitions might be expected to mirror trends in regional populations in Australia. Indicative is the number of ignitions in the Australian Capital Territory which have increased steadily since around 1940 (Williams *et al*. 2009), presumably partly because of population increases and changes in regulations and land use, but also possibly reflecting changes in ignition detection methods.

People also play a major role in preventing and suppressing ignitions, although overall effectiveness is debated (Miyanishi and Johnson 2001). Cary *et al*. (2009), presenting results from five landscape-scale simulation models from around the world, argue that variation in weather and ignition management are more important than variation in fuel management in determining area burned in fire-prone ecosystems. Ultimately though, the success of ignition management, which might take the form of rapid attack of fires, education programs aimed at preventing fire ignitions and restricting access into vegetated landscapes during periods of higher fire danger, will depend on interactions with weather and amount and availability of fuel (Cary *et al*. 2009). Thus, future management success will not only depend on technological advances, but on future trends in the weather and in fuel dynamics. Notwithstanding this, our capacity to suppress fires will remain critical to determining future fire regimes (Cary 2002).

Global change effects on fire regimes

Insights from palaeoecological studies

Fire has been present on earth since at least the Silurian Period (444–416 Ma ago) (Glasspool *et al*. 2004), soon after the origin of terrestrial vegetation (Bowman *et al*. 2009). Fire activity has fluctuated with variations in climate, levels of atmospheric O_2 and CO_2, ignition rates and the composition of vegetation (Bowman *et al*. 2009). Varied sources such as charcoal in sediments and soils, and fire scars in dated series of tree rings, can be used to infer past patterns of fire activity, providing insights ranging from centuries to millions of years. In Australia, evidence of past fire regimes is largely confined to interpretation based on patterns of variation in charcoal deposits (see Mooney *et al*. this volume). Dendrochronological evidence is generally restricted to a smaller number of studies of fire scars in trees (e.g. Banks 1989; Brookhouse 2006) and 'bands' on grass trees (e.g. Ward *et al*. 2001; Miller *et al*. 2007), with interpretations focusing primarily on human ignition rates rather than climate effects.

Charcoal records (see Lynch *et al*. 2007 and Mooney *et al*. 2011 for comprehensive reviews) provide evidence for the occurrence of fire in Australia throughout the Tertiary Period (65–2.6 Ma ago), though sources of early data are highly limited (Kershaw *et al*. 2002). Throughout the Quaternary Period (2.6 Ma ago–present), fire activity in Australia appears to have been indirectly controlled by fluctuations in global temperature and its influence on vegetation productivity throughout glacial-interglacial cycles. Fire activity was less evident during cold glacial intervals but it increased during warmer interglacials (Mooney *et al*. 2011). Lynch *et al*. (2007) emphasised the importance of interactions between cyclical patterns of dryness and regional vegetation characteristics given that in drier, glacial periods, fire activity appeared to decrease in arid areas due to assumed reductions in vegetation cover and fuel, but increased in comparatively wetter areas where fuel was presumably less limiting. Importantly, greater fire activity has been identified during periods of climatic change at various times in the past (Black and Mooney 2006; Lynch *et al*. 2007). For example, peaks in charcoal have been associated with periods of frequent ENSO episodes (Lynch *et al*. 2007), which are assumed to have maximized potential for fire through the coincidence of fuel availability, suitable fire weather and ignitions. Mooney *et al*. (2011), however, could not find clear evidence for this historical relationship between ENSO and biomass burning.

The inferred interrelationship between humans, fire and climate in the Australian palaeo-record is complex and variable. In the pre-European period, human influences are likely to have been strongly dependent on variations in vegetation characteristics and population density (Enright and Thomas 2008). Lynch *et al.* (2007) reviewed charcoal evidence indicating 'clear regional shifts' in fire activity coinciding with assumed timing of initial human occupation of the continent and at the time of European colonization. In contrast, Mooney *et al.* (2011) found no evidence for changed fire activity at a continental scale around the time of Aboriginal arrival. Nevertheless, human influences on fire regimes may have been more prominent in close proximity to locations of permanent water and travel routes, particularly in vast desert landscapes where fire regimes were predominantly controlled by the weather driven cycles of fuel availability and ignition from lightning (Bliege Bird *et al.* 2008). Effects of people and climate on fire in the past are explored in further detail by Mooney *et al.* (this volume).

Palaeo-perspectives on fire, while not unequivocal, indicate that fire regimes can vary in complex ways consistent with the notion of varying modes of limitation of fire occurrence (Figure 3). Climatic variation emerges from the palaeo-record as an overriding influence on past fire activity via direct and indirect influences, providing some insights into possible future fire regimes. The level of human influence on past fire regimes, as interpreted from palaeoecological evidence, remains controversial (Mooney *et al.* 2011, Mooney *et al.*, this volume; Pinter *et al.* 2011). Nevertheless, the future may be characterised by novel combinations of climate, vegetation and human influences such that inferences from the past may not be wholly applicable in the future.

Effects on Future Fire Regimes

Williams *et al.* (2009) and Bradstock (2010) have presented scenarios for global change impacts on drivers of fire regimes for a range of representative ecosystems in Australia (Table 1). Their approach involved identifying likely future trends in ignition, weather and fuel, across a range of representative ecosystems and generating hypotheses about likely trends in fire regimes. Given uncertainty in greenhouse gas emissions, future climates and effects on drivers of fire activity, there

is necessarily considerable uncertainty in projections of future fire. The uncertainty is unavoidable and is a characteristic of many facets of our understanding of fire and other natural processes, irrespective of whether considering the past, present or future (Kershaw *et al*. 2002; Cary 2002).

Recent projections indicate that increased temperature, and modified levels of precipitation and evaporation, will generally result in: (i) increased frequency of days with higher fire danger across most ecosystems, although the increase may be small for cool temperate wet sclerophyll forests; and (ii) generally decreased grass and litter loads resulting from declining precipitation (Williams *et al*. 2009, Bradstock 2010) (Table 1). Elevated CO_2 may result in: (i) further decreases in grass and herb production in tropical open forests and arid woodlands, given woody growth may be favoured (Morgan *et al*. 2007); and (ii) increased litter production in temperate forests (Table 1). Invasive or locally introduced species are already a feature of most ecosystems (Rossiter *et al*. 2003; Clarke *et al*. 2005) (Table 1) and they have the potential to significantly alter flammability characteristics in the future as their distributions widen. Anthropogenic ignitions are expected to increase in forests and decline in temperate grassy woodlands, largely reflecting expected population density trends.

Likely future trends in key drivers of fire activity (Table 1) are expected to translate into altered fire regimes in complex ways in any particular ecosystem because various effects can be synergistic, antagonistic or orthogonal in nature. According to Williams *et al*. (2009) and Bradstock (2010), the interval component of future fire regimes will depend on interacting influences on biomass dynamics (B) and rates of recurrence of weather causing high availability of fuel (A) and high rates of fire spread (S) (Figure 6), although rates of ignition (I) will remain critically important.

In arid and temperate grassy woodlands, increased dryness (Pausas and Bradstock 2007) and elevated CO_2 may lengthen the fire interval because of declining fuel loads, although increases in biomass of exotic species, particularly buffel grass in arid woodlands, may act to counter this effect. Intervals may shorten due to increased fire danger in temperate grassy woodlands but not arid woodlands where meteorological conditions amenable to widespread fire already occur frequently (Williams *et al*. 2009, Bradstock 2010). Such predictions contrast with those by Krawchuck *et al*.

(2009*a*) who predict a 'retreat' of fire across temperate and tropical woodlands in Australia in coming decades. Such contrasting trends reflect differences in the quasi process-based approach used here compared with global, statistical modelling approaches used by Krawchuk *et al.* (2009*a*).

In temperate wet and dry sclerophyll forests, decreased amounts of accumulated litter resulting from lower productivity in drier conditions may act to lengthen fire intervals, although higher atmospheric CO_2 could potentially offset this effect because of higher productivity of litter and lower decomposition of litter resulting from lower palatability to decomposers (Hovenden and Williams 2010; Williams *et al.* 2009; Bradstock 2010). However, there will be a tendency for fire intervals to shorten because of the likely increased incidence of more severe fire weather, particularly in temperate dry sclerophyll forests (e.g. Bradstock *et al.* 2009) and because of higher human populations. There is, however, a limit to intervals becoming shorter because fuel may become somewhat limiting (Cary 2002). The response of tropical open (dry sclerophyll) forests will likely be determined by a similar combination of factors affecting woodlands: (i) increased dryness and elevated CO_2 decreasing grassy biomass and lengthening fire interval (see Gill *et al.* 2009 for relationship between area burned and rainfall in tropical savannas); and (ii) expansion of highly flammable gamba grass causing a tendency toward shorter fire intervals. Sufficient periods of weather conditions conducive to burning large areas of tropical open forest ecosystems already occur every year in the dry season, thus increased fire danger is unlikely to result in shorter fire intervals. Increased ignition from anthropogenic sources, and probably lightning, will likely shorten intervals between fires.

The fire regime projections of Williams *et al.* (2009) and Bradstock (2010) are less detailed than earlier projections quantifying intensity, season and fire interval (Cary 2002). However, the recent projections are more comprehensive given they incorporate more of the key global warming and global change effects on drivers of fire occurrence and behaviour. Cary (2002) focused on the effects of changes in ambient and antecedent weather, ignoring likely trends in fuel load, vegetation type and ignition frequency. Over time, projections incorporating greater representation of processes

affecting spatial and temporal fire dynamics are likely to become available, allowing exploration of increasingly sophisticated questions involving interactions of greater complexity. Nevertheless, given the uncertainty in projections for underlying processes, projections for the nature of fire regimes will only ever define a series of possible outcomes. A definitive understanding of changes in fire regimes will most likely only ever result from careful monitoring of fire regimes, as has been identified more generally by Gill *et al*. (2002).

Table 1. Global change scenarios in case studies in differing Australian ecosystems. Climatic predictions are 2070 (50th percentile) scenarios from CSIRO (2007) for Darwin (TF), Alice Springs (AW), Dubbo (TGW), Adelaide[a] (TGW - Mediterranean), Sydney (DSF), Perth[b] (DSF - Mediterranean) and Hobart (WSF). Fire danger scenarios based on Williams *et al.* (2001)[1] and Lucas *et al.* (2007)[2] for 2050. (Modified from Bradstock 2010).

Global change attribute	Tropical open forest (TF)	Arid woodlands (AW)	Temperate grassy woodlands (TGW)	Temperate dry sclerophyll forests (DSF)	Cool temperate wet sclerophyll forests (WSF)
Rainfall (% change)	-1	-9 to -17	- 4 to -7 -7 to -13[a]	- 4 to -8 -11 to -19[b]	-3 to -6
Temperature (^{o}C change)	+1.7 to +3.2	+1.9 to +3.7	+1.7 to +3.3 +1.5 to +2.8[a]	+1.6 to +3.0 +1.4 to +2.7[b]	+1.1 to +2.1
Evaporation (% change)	+5 to +10	+4 to +7	+4 to +9 +3 to +6[a]	+5 to +9 +4 to +7[b]	+5 to +10
Fire Danger (Very High and Extreme days p.a. - Pre 2009 Fire Danger Rating scale)	Increase[1]	Increase[1]	+4.4 to +20.8[2] +1.6 to +11.5[2a]	+0.4 to +6.6 (Sydney)[2] Increase likely (Perth)[1]	0 to +0.2 (Hobart)[2]
Sensitivity (direction of change in mass) of main fuel types to: **A**) climate change; and **B**) elevated CO_2	Annual grasses **A**) decrease **B**) decrease	Perennial grasses and annual herbs/grasses **A**) decrease **B**) decrease	Perennial grasses and annual herbs/grasses **A**) decrease **B**) decrease Woody plant litter **A**) decrease **B**) increase	Woody plant litter and shrub crowns **A**) decrease **B**) increase	Woody plant litter **A**) decrease **B**) increase
Introduced Plant Types	Gamba grass	Buffel Grass	Tree plantations	Exotic grasses – Mediterranean areas	
Trend in ignitions		+ anthropogenic	- anthropogenic	+ anthropogenic	+ anthropogenic

Woodland

Forest

c ← **WSF** → li
    ← **DSF** →

c g   e
e ← **TGW** ⇄ ←**AW** ⇄ c g

e ←**TF** ⇄ c g

Effect of biomass growth (B)

1   5 10   100
Potential IFI (years)

1   5 10   100
Potential IFI (years)

AW
f←**TGW**

TF   f ← **DSF**   **WSF**

Effect of fire weather (A+S)

1   5 10   100
Potential IFI (years)

1   5 10   100
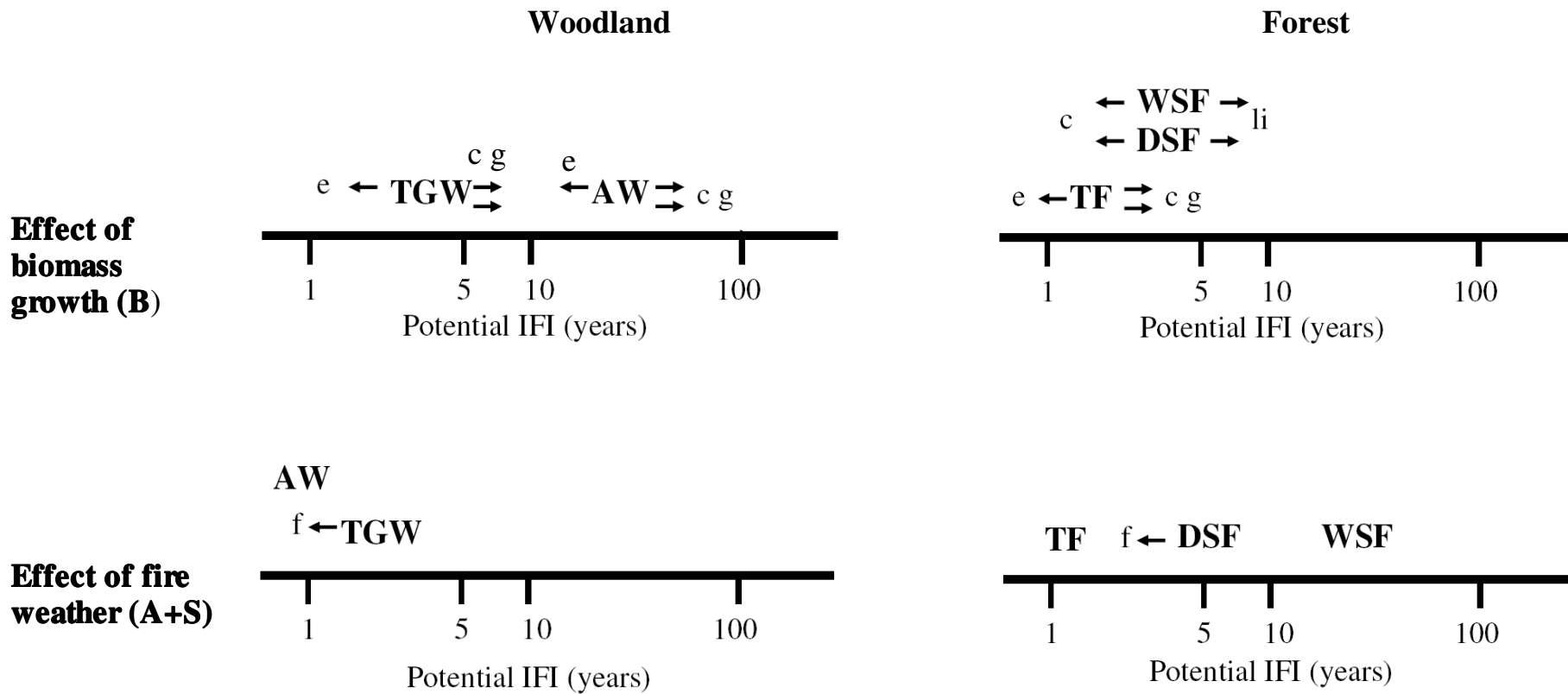Potential IFI (years)

Figure 6. Effects of global change on factors governing fire regimes in woodland (AW – arid woodland; TGW – temperate grassy woodland), and forest (TF – tropical open forest; DSF – temperate dry sclerophyll forest; WSF – temperate wet sclerophyll forest). Position of bold symbols indicate likely contemporary inter-fire interval (IFI) based on that influence alone. Arrows indicate direction of possible climate/global change effects according to projected changes in biomass growth (B) and fire danger (A + S). Potential climate/global change effects are indicated by various arrows: Fire danger (f); Grass/herb growth (g); Elevated CO_2(c); Litter accumulation (li); and Exotic species (e). (Modified from Bradstock 2010).

Resultant effects on plant assemblages and diversity

Species or functional types comprising plant assemblages are unlikely to exhibit synchronous responses to potential changes in climate and fire regimes. Broad aspects of plant dynamics in response to variation in fire interval are reasonably well understood (Noble and Slatyer 1980; Gill 1981; Bradstock *et al*. 2002; this volume), providing valuable insights for predicting ecological impacts of future fire regimes. At one level, an understanding of the effects of fire regimes on biodiversity requires the identification of taxa, a level of classification required to satisfy various legal requirements for conservation of species and evaluation of management actions. Alternatively, the concept of 'functional types' of species, for example classifying plant species as 'seeders' or 'sprouters' together with information on life-stage markers (*e.g.* Noble and Slatyer 1980; Pausas *et al*. 2004; Clarke *et al*. 2005), has been widely used to seek generalisations about plant distributions in relation to fire regimes, especially inter-fire intervals. The simplest case of a functional type is that of woody 'seeder' species with seed stored in canopies only. This type occurs in many Australian shrublands and forests. A lengthening in the interval between fires of sufficient intensity to kill populations may result in plants dying out, while if the intervals are too short then the species may become locally extinct also (see Gill 2008). The remainder of the species in the community may continue to persist, depending on their particular fire response and life history pattern. The functional-type approach applied across landscapes or regions is useful for understanding effects of altered fire regimes because it is independent of taxonomic identity and thus it provides a focus on process.

Future distributions of functional types will depend also on the direct effects of global change (Dunlop and Brown 2008). Thus, an outstanding question in relation to fire and global change is concerned with what will be the combined influence on distributions of different functional types? A comprehensive answer is, of course, unattainable at this point in time given knowledge about each dimension of the problem (effects of change on fire regimes; effects of change on distributions) is still fragmentary. Nevertheless, there are valuable insights into types of interactions that might occur. Williams *et al*. 2009 report that in the Sydney Basin, where fire intervals are expected to become

shorter in the future (Bradstock *et al.* 2008; Bradstock *et al.* 2009), temperature and moisture availability are partly responsible for distributions of plant functional types. They speculate that increasing temperature might: (i) be disadvantageous to resprouting species, which are likely to be more resilient under a regime of more frequent fire; and (ii) promote obligate seeder species, a functional type most likely to be most sensitive to increased fire frequency. Thus, 'climate change has the potential to shift vegetation composition toward functional types that are more sensitive to any shift in length of between-fire interval' (Williams *et al.* 2009).

Other relevant functional classifications exist, including recognising the importance of 'fuel taxa' (Gill 1999). While most species make little contribution to the species assemblage with respect to biomass, abundance (e.g. Whittaker 1965) or the fuel array at any one place – because they are rare – a few species or taxa are common and may dominate. Common examples include certain grasses that may make up the bulk of the fuel in any one circumstance (*Astrebla*, *Themeda*, *Tetrarrhena*, *Stipa*, *Triodia*) and litter fuels which, in Australia, commonly arise from various eucalypts (*Eucalyptus sensu lato*). 'Fuel' may be seen as applying to individual plants, as well as species, and relevant to understanding the evolution of species in fire-prone environments (Bond and Midgely 1995; Schwilk and Kerr 2002). Changes in occurrence, abundance or dominance of 'fuel taxa', arising from altered future fire regimes and from the effect of global change directly (as discussed above), could potentially generate strong positive or negative feedbacks. Therefore, the interacting effects on fire regimes and functional types (including fire response, life form and fuel types), while impossible to predict, will play out across current and future fire-prone Australian landscapes, providing rich opportunities to explore and understand this fascinating dynamic.

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