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Implications of changing climate and atmospheric CO_2 for grassland fire in south-east Australia: insights using the GRAZPLAN grassland simulation model

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Abstract. Climate and fuel characteristics influence fire regimes, and both need to be realistically considered in bushfire projections. Previous south-eastern Australian studies have assumed maximum grassland fuel curing (100%) and average fuel load (4.5 t ha^{-1}). This study is the first to include daily fuel curing and load dynamics, derived from the agricultural pasture growth model GRAZPLAN, in projections of Grassland Fire Danger Index (GFDI) and potential fire-line intensity for future climate–CO_2 combinations, and for alternate grasslands in the Canberra, Sydney and Melbourne regions. Climate-change projections were characterised by warmer, drier conditions, with atmospheric CO_2 concentrations increasing for longer future timeframes. Projected shifts in GFDI and potential fire-line intensity arising from future climate–CO_2 combinations were small compared with initial difference arising from using realistic GRAZPLAN-derived curing and fuel load values (compared with constant curing and fuel load) for grass dynamics, and this has important implications for the interpretation of earlier studies. Nevertheless, future grass curing and GFDI generally increased and fuel load generally decreased. The net effect on modelled future fire-line intensity was minimal because higher fire danger, and hence spread rate, was often largely compensated for by lower fuel load across the range of modelled grassland types and locations.

Additional keywords: curing, fire-line intensity, fuel load, GFDI.

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Introduction

Generally, climate, fuel quantity and availability, and rates of natural and anthropogenic ignitions determine fire regimes (Archibald *et al.* 2009; Parisien and Moritz 2009; Bradstock 2010; Krawchuk and Moritz 2011). Most fire activity occurs during hot, windy conditions and when there are sufficient amounts of available fuel for fire ignition and propagation. Understanding interactions between these controlling factors for alternative combinations of climate and atmospheric CO_2 will improve projections of future fire behaviour.

In Australia, fires in grasslands are common and can result in the loss of life, property, agricultural infrastructure, pastures and livestock (Cheney and Sullivan 1997). The Grassland Fire Danger Index (GFDI) is used to forecast potential grassland fire activity and the potential for successful fire suppression. GFDI calculations rely on ambient weather, and on grass curing – a measure of dryness and hence availability of fuel (McArthur 1966, 1973; Noble *et al.* 1980). Grassland fire intensity (Byram 1959) depends on available fuel and on the rate of fire spread, which in turn is a function of weather, curing and grassland moisture condition (Cheney *et al.* 1998). The biological inputs of curing and fuel load are ideally estimated daily, and are dependent on interactions between dominant grassland type, soil moisture, time of year and recent weather.

Calculating the extent of grassland fire risk retrospectively is difficult owing to the absence of archived grass fuel and curing records (see Gill *et al.* 2010). Further, projections of changes in grassland fire danger (e.g. Hennessy *et al.* 2005; Lucas *et al.* 2007; Pitman *et al.* 2007) and fire behaviour (Sullivan 2010) under future possible climates have assumed a constant 100% curing at all times. In reality, the actual extent of curing will reflect the physiology of the dominant grassland type, soil attributes, slope and aspect, and recent weather, with periods of 100% grass curing, and the potential for extreme fire conditions, generally being limited to the warmest, driest months.

The potential for fire suppression, property damage and risk to human health in grassland fires depends, partly, on fire intensity. Fire intensity (Byram 1959) is determined by (i) rate of fire spread (Cheney *et al.* 1998), which is influenced by GFDI and hence by weather and curing; and (ii) fuel load, influenced by atmospheric CO_2 concentration and weather, among other factors. It has been demonstrated empirically that changes in temperature, rainfall and atmospheric carbon dioxide (CO_2) concentrations under future climates may alter grassland fuel-load accumulation and decomposition processes (e.g. Howden *et al.* 2008; Cullen *et al.* 2009; Hovenden and Williams 2010), indirectly affecting fire intensity. Therefore, future grassland fire intensity will reflect complex interactions between fuel dynamics and fire spread rate.

Temporal dynamics of grassland curing and fuel load can be derived from the agricultural pasture model GRAZPLAN (see Gill *et al.* 2010). Given GRAZPLAN relies on physiological processes to model the growth of several key pasture types (Donnelly *et al.* 1997; Moore *et al.* 1997), it can be used to simulate changes in grass growth in response to climate, both retrospectively and for alternative future climates. Daily calculations of curing and fuel load available from GRAZPLAN can facilitate estimations of historical and future daily GFDI – and potential intensity of grassland fires – that are more realistic than calculations derived from predetermined maximum curing and average fuel load model inputs. For example, in Canberra, in the Australian Capital Territory, calculations with grass curing set at 100% and fuel loads set at 4.5 t ha^{-1} produce daily GFDI and fire-line intensity values between two (summer) and twenty (winter) times as high as those incorporating variable daily curing and fuel load derived from GRAZPLAN (Gill *et al.* 2010).

This study extends the work of Gill *et al.* (2010). Our first objective was to determine whether differences between historical distributions of GFDI and fire-line intensity – arising from GRAZPLAN-derived curing and fuel load model inputs, and those arising from commonly used, predetermined values (100% curing; 4.5 t ha^{-1} fuel load) – are more general for south-eastern Australia than just Canberra (Gill *et al.* 2010). The main objective of the present study was to then determine the effect of changed climate and atmospheric CO_2 combinations (historical; a mid-range climate change for 2030, A1B; a moderate change for 2070, B1; and a much greater change for 2070, A1FI) (IPCC 2000) on GRAZPLAN-derived grass curing, fuel load, and thus GFDI and potential fire-line intensity. The extent that these effects can be generalised across different grassland types (native perennial, exotic perennial and exotic annual) and alternative locations in south-eastern Australia was also explored.

Methods

Study locations

South-east Australia has a temperate climate, with high variability in rainfall and periods of drought reflecting effects from the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM) (Australian Bureau of Meteorology, http://reg.bom.gov.au/climate/glossary/elnino/elnino.shtml, accessed 15 May 2012). For this study, three south-eastern Australian locations, each partly surrounded by pasture grasslands (Canberra, Melbourne and Sydney), with contrasting overall and seasonal patterns in climate, were selected (Fig. 1). Grasslands have greater biomass closer to the coastline (Sydney, Melbourne), where rainfall is higher and generally more reliable, and soil fertility is moderate.

The GRAZPLAN model

The GRAZPLAN grassland and water-balance simulation model (Donnelly *et al.* 2002) uses daily time steps to simulate grass physiological processes of growth, death and decay. In GRAZPLAN, annual and perennial pasture dynamics – including pasture phenology, seed dormancy release and rates of assimilation and respiration – are determined by daily maximum and minimum temperature and rainfall and atmospheric CO_2 concentration, soil hydrological properties and management practices (Moore *et al.* 1997; Moore and Lilley 2010). In our study, soil–water balances reflected climatic conditions, particularly rainfall, and the hydrological attributes of a typical soil for pasture grasses at each location (Table 1).

Our study simulated the daily growth of three monospecific grassland types with contrasting growth attributes. In all simulations, it was assumed that livestock grazing, cutting and fertilisation, which affect the growth dynamics of each grassland type, were absent. Grasslands modelled were:

(1) Native perennial grass – *Austrodanthonia* H.P. Linder, a genus of native, perennial grasses present in all locations (Burbidge and Gray 1970; Walsh and Entwisle 1994; Australian Biological Resources Study 2005);
(2) Exotic perennial grass – the introduced pasture grass *Phalaris aquatica* L., present in rural settings and urban parkland; and
(3) Exotic annual grass – the widespread introduced pasture grass *Lolium rigidum* Gaudin (annual ryegrass).

Alternative climates

For each of the three study locations, patched point historical daily weather datasets (Jeffrey *et al.* 2001) were used as input for GRAZPLAN modelling. These datasets are composed of observational weather data (1 January 1965 to 30 April 2011) collected at airport weather stations at Canberra, Melbourne and Sydney by the Australian Bureau of Meteorology. Missing weather records are estimated from nearby stations by interpolation techniques.

Climate projections derived from a suite of Global Circulation Models (GCMs) indicate a general trend to warmer and drier climates in south-eastern Australia, with the extent of change varying seasonally and by location (CSIRO and Australian Bureau of Meteorology 2007) (Table 2). Daily weather was derived for alternative future climates by applying the 50th percentile (median) projected seasonal changes in temperature, rainfall, wind speed, relative humidity and solar radiation to each historical daily weather value (1 January 1965 to 30 April 2011) for each location. Projected atmospheric CO_2 concentrations from the Bern Carbon Cycle model (http://www.ipcc-data.org/ancilliary/tar-bern.txt, accessed 15 May 2012) were used. Effects of altered CO_2 concentration on plant growth that are represented in GRAZPLAN are: (i) reduced transpiration due to partial stomatal closure; (ii) a direct CO_2 fertilisation effect; (iii) an increase in specific leaf area and (iv) decreased leaf nitrogen content. Effects of changes in temperature and rainfall on grassland physiology are also incorporated in the model (Moore and Lilley 2010).

Atmospheric CO_2 and climate combinations included in the analysis were: (i) historical weather data with 350 ppm

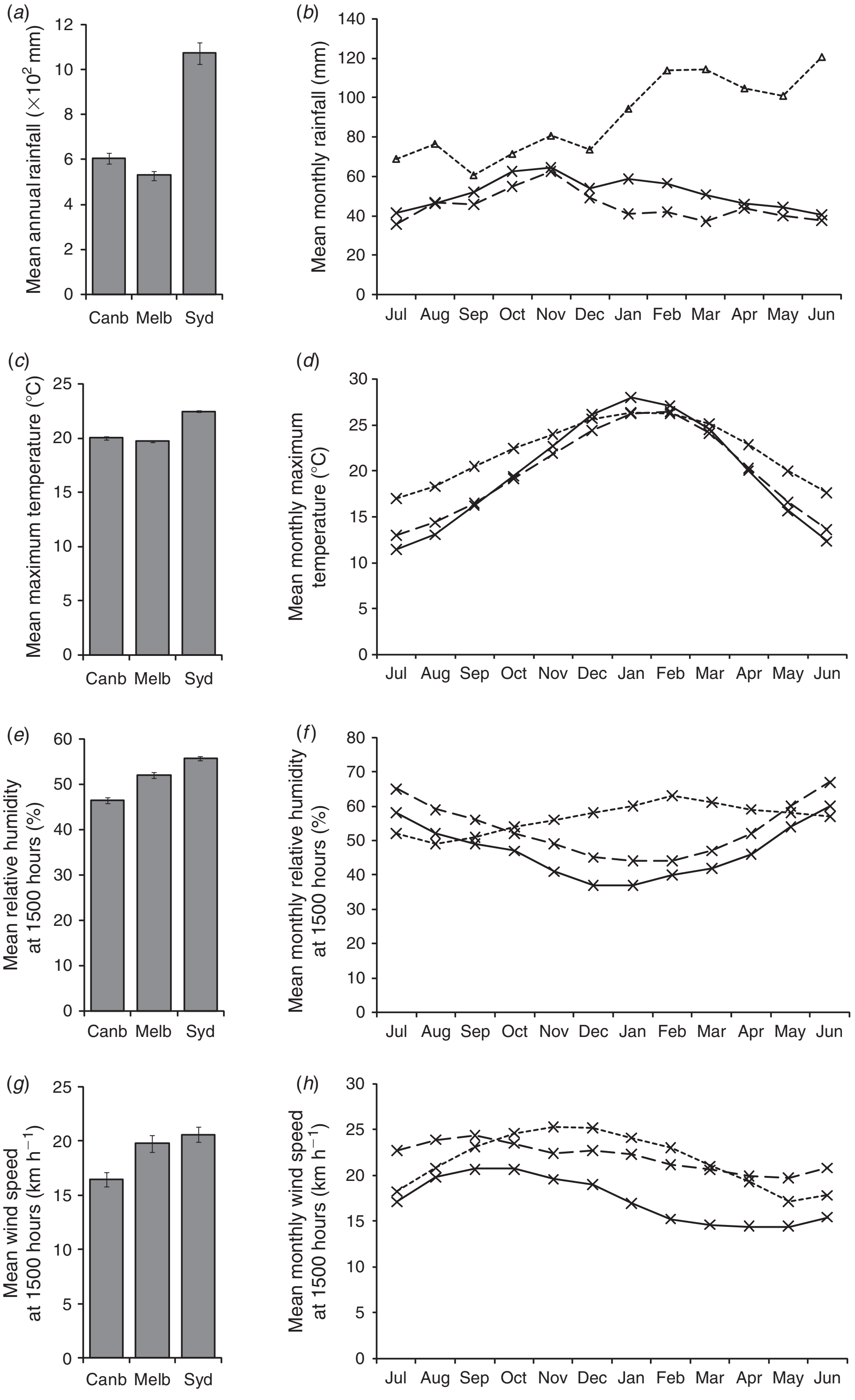

Fig. 1. Mean rainfall (*a*, annual; *b*, monthly), temperature (*c*, annual; *d*, monthly), relative humidity (*e*, annual; *f*, monthly) and wind speed (*g*, annual; *h*, monthly) for Canberra Airport (solid line, 1939–2010); Melbourne Airport (dashed line, 1970–2010) and Sydney Airport (dotted line, 1939–2010) (data from www.bom.gov.au, accessed 15 May 2012).

Table 1. Attributes of soils representative of pasture grasses at Canberra, Melbourne and Sydney

	Location of soil sample	Soil type	Plant-available water holding capacity (PAWC)	Reference
Canberra	Crace	Podosol	124 mm	Stace *et al.* (1968); Isbell (1996)
Melbourne	Mount Derrimut	Sodosol	136 mm	Stace *et al.* (1968)
Sydney	Hornsby	Kandosol	93 mm	Johnston *et al.* (2003); www.asris.csiro.au (accessed 15 May 2012)

Table 2. Median (50th percentile) projected seasonal shifts in climate for Canberra, Melbourne and Sydney, Australia, derived from a suite of Global Circulation Models (GCMs) for 2030 A1B (a mid-range climate change for 2030), 2070 B1 (a moderate change for 2070) and 2070 A1FI (a much greater change for 2070) emission scenarios

Derived from: Climate change in Australia: technical report 2007, appendix B (CSIRO and Australian Bureau of Meteorology 2007)

		2030 A1B				2070 B1				2070 A1FI			
		Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
Temperature (°C)	Canberra	+1.0	+0.9	+0.8	+1.0	+1.7	+1.5	+1.3	+1.7	+3.2	+3.0	+2.5	+3.3
	Melbourne	+1.0	+0.8	+0.7	+0.9	+1.6	+1.4	+1.1	+1.5	+3.1	+2.7	+2.2	+2.9
	Sydney	+1.0	+0.9	+0.8	+1.0	+1.6	+1.5	+1.4	+1.7	+3.1	+3.0	+2.6	+3.3
Precipitation (%)	Canberra	0	−2	−5	−6	0	−3	−9	−10	+1	−6	−16	−19
	Melbourne	−1	−2	−4	−7	−2	−2	−7	−11	−4	−5	−12	−21
	Sydney	+1	−2	−5	−6	+1	−3	−9	−9	+2	−6	−16	−17
Wind speed (%)	Canberra	+1	−2	0	−1	+2	−4	−1	−2	+4	−8	−1	−3
	Melbourne	0	−3	+1	0	0	−4	+1	−1	−1	−1	−8	+2
	Sydney	+3	−2	−1	0	+4	−3	−2	−1	+8	−5	−3	−1
Solar radiation (%)	Canberra	+0.5				+0.7				+1.4			
	Melbourne	+0.8				+1.3				+2.6			
	Sydney	+0.3				+0.5				+0.9			

CO_2 and (ii) weather datasets representing three projected future climates (IPCC 2000), namely 2030 under the A1B SRES emissions scenario with 450 ppm CO_2; 2070 under the B1 emission scenario with 518 ppm CO_2 and 2070 under the A1FI emission scenario with 707 ppm CO_2. The B1 emission scenario represents a moderate change in climate as it assumes the use of clean and resource-efficient technologies, whereas the A1FI emission scenario represents a much greater change in climate given it assumes the continued use of fossil-fuel-intensive technologies. The A1B emission scenario represents a mid-range change in climate as it assumes a balanced use of fossil-intensive and non-fossil energy sources and technologies.

Simulations and analyses

Simulations were carried out using the *AusFarm* software package, of which GRAZPLAN is a component (described at www.grazplan.csiro.au, accessed 15 May 2012). For each location, grass dynamics were simulated using historical and projected levels of atmospheric CO_2 and related climates. Analyses were performed on output data for the period 1 January 1972 to 30 April 2011, with the earlier period (1 January 1965–1 January 1972) used to initialise model conditions. For each location and climate, daily curing percentages, total grass fuel loads (live + dead standing + litter) ($t\,ha^{-1}$) and GFDI at 1500 hours and potential fire-line intensity ($kW\,m^{-1}$) were derived from a combination of GRAZPLAN outputs and daily weather.

Daily GFDI was calculated according to McArthur (1973), as undertaken regionally by the Australian Bureau of Meteorology for operational purposes (Eqn 1, Noble *et al.* 1980):

$$\mathrm{GFDI} = 2.0 \times \exp(-23.6 + 5.0 \times \ln(curing) + 0.0281 \times T - 0.226 \times \sqrt{RH} + 0.663 \times \sqrt{u}) \quad (1)$$

where *curing* is the proportion of dead aboveground grass material (%); T is the temperature at 1500 hours (°C); RH is relative humidity at 1500 hours (%); and u is wind speed at 1500 hours ($km\,h^{-1}$). For each unique combination of location, grassland and climate–atmospheric CO_2, daily GFDI values were calculated using daily curing values derived from GRAZPLAN. GFDI was also calculated for historical climate and atmospheric CO_2, for each location and grassland, assuming a constant 100% curing (Hennessy *et al.* 2005; Lucas *et al.* 2007; Pitman *et al.* 2007).

Daily potential fire-line intensity ($kW\,m^{-1}$) was calculated according to Byram (1959) (Eqn 2).

$$\mathrm{Intensity} = H \times w \times r \quad (2)$$

where H is the heat yield and equals 16 150 $kJ\,kg^{-1}$, representing the average of values for a range of grassland types (Cheney and Sullivan 1997); w is the fuel load ($kg\,m^{-2}$) (total aboveground herbage mass) derived from GRAZPLAN; and r is the forward rate of spread in undisturbed grasslands ($m\,s^{-1}$), which is calculated from curing, wind speed and dead fuel moisture content using the equations of Cheney *et al.* (1998) for undisturbed pastures.

Initially, for each location and grassland, monthly distributions of historical GFDI and potential fire-line intensity resulting from GRAZPLAN-derived curing and fuel load were compared with distributions resulting from constant curing (100%) and fuel load (4.5 t ha^{-1}). GRAZPLAN-derived curing and fuel load were then used to derive the 50th (median) and 95th percentile monthly curing, GFDI, fuel load and potential fire-line intensity, and these were compared graphically between locations, grasslands and alternative climate–atmospheric CO_2 combinations. For each grassland and location, and for the months of October–February (when the majority of fires occur), Kolmogorov–Smirnov goodness-of-fit tests compared monthly curing, GFDI, fuel load and potential fire-line intensity distributions between climate and CO_2 combinations.

To determine the individual influences of weather (temperature and moisture) and atmospheric CO_2 concentrations on curing, single-factor analyses of variance (ANOVAS) compared daily outputs from additional simulations where changes were made only to weather or CO_2 concentrations.

Results

Effect of variable versus constant fuel load and curing

For each location, large differences were evident between distributions of monthly median GFDI that were determined from variable (GRAZPLAN-derived) and constant curing (Fig. 2). Monthly median GFDI calculated with constant curing was always higher than GFDI derived from GRAZPLAN-derived curing, particularly in cooler months (May to November) when curing is normally at a minimum. At all locations, assuming variable curing and fuel load (GRAZPLAN-derived), peak monthly median GFDI values occurred later for native perennial grasslands, and earlier for both exotic grasslands. Peak monthly median GFDI values were lowest for the native perennial grasslands (Fig. 2).

Large differences were also evident between distributions of monthly median potential fire-line intensity derived from variable (GRAZPLAN-derived) and constant curing and fuel load (Fig. 2). Again, differences were largest in cooler months when both curing and fuel load are lower. At all locations, the native perennial grasslands had the lowest peak monthly median potential fire-line intensity. Potential fire-line intensity peaked latest in native perennial and exotic annual grasslands in Sydney, and in native perennial grasslands in Canberra and Melbourne (Fig. 2).

Effects of changing climate and atmospheric CO_2 on curing

GRAZPLAN-derived curing varied between months, alternative climate and atmospheric CO_2 combinations, grasslands and locations. Monthly 50th and 95th percentile curing was generally predicted to increase as climates became warmer and drier (2030 A1B, 2070 B1 and 2070 A1FI), compared with the historical climate, particularly during spring and early summer (September–January) in Canberra and Melbourne, and during autumn (February–May) in Sydney (Kolmogorov–Smirnov (KS), $n = 1167$; $KS > KS_{crit} = 0.04$; $\alpha = 0.05$) (Fig. 3). Increases in monthly curing were generally predicted to be greater for 2070, compared with 2030. The main exception to this overall pattern was the exotic perennial grassland in Sydney, which was characterised by declining curing, particularly during spring, for the warmer, drier future climates.

For each grassland and location, changes in temperature and moisture determined curing, with atmospheric CO_2 concentration having no significant effect (single-factor ANOVA: comparison between curing across CO_2 concentrations, d.f. = 3; $P > 0.05$; $F < F_{crit} = 2.6$; comparisons between curing across climates (constant CO_2), d.f. = 3; $P < 0.05$; $F > F_{crit} = 2.6$).

Effects of changing climate and atmospheric CO_2 on GFDI

Modelled GFDI varied between months, alternative climate and atmospheric CO_2 combinations, grasslands and locations. As changes in atmospheric CO_2 concentration had no significant effect on curing, changes in GFDI reflected direct climate effects only. Monthly 95th percentile GFDI was generally predicted to increase as climates became warmer and drier (2030 A1B, 2070 B1 and 2070 A1FI), compared with the historical climate, particularly in the warmer months (November to March) ($n = 1167$; $KS > KS_{crit} = 0.04$; $\alpha = 0.05$) (Fig. 4). Increases in monthly 95th percentile GFDI were generally predicted to be greater for 2070, compared with 2030. Monthly 50th percentile GFDI also increased but the shifts were generally less pronounced, in absolute terms. The main exception to this overall pattern was the exotic perennial grassland in Sydney, which was characterised by declining monthly GFDI, particularly during summer and autumn, for the warmer, drier future climates.

Effects of changing climate and atmospheric CO_2 on grass fuel load

For the exotic annual grasslands at all locations and the exotic perennial grasslands in Canberra and Melbourne, the mean fuel load between October and April, when the majority of fire activity occurs, was a good approximation for the assumed mean fuel load of 4.5 t.ha^{-1} used in earlier studies, whereas it was consistently lower for the native perennial grasslands in all locations and the exotic perennial grasslands in Sydney. Modelled grass fuel load reflects complex interactions between the direct positive effects of CO_2 fertilisation, and the indirect usually negative effects of temperature and moisture stress on plant physiological processes, with these effects generally increasing as climates warm and dry (Fig. 5). Fuel load varied between months, alternative climate and atmospheric CO_2 combinations, grasslands and locations (Fig. 6). Monthly 50th and 95th percentile grass fuel load was generally predicted to decline at least for a significant number of months ($n = 1167$; $KS > KS_{crit} = 0.04$; $\alpha = 0.05$). Declines in fuel load again were generally predicted to be greatest for the 2070 AIFI climate–CO_2 combination. The overall trend was reversed to some extent in Canberra for native perennials and for exotic annuals, particularly during spring.

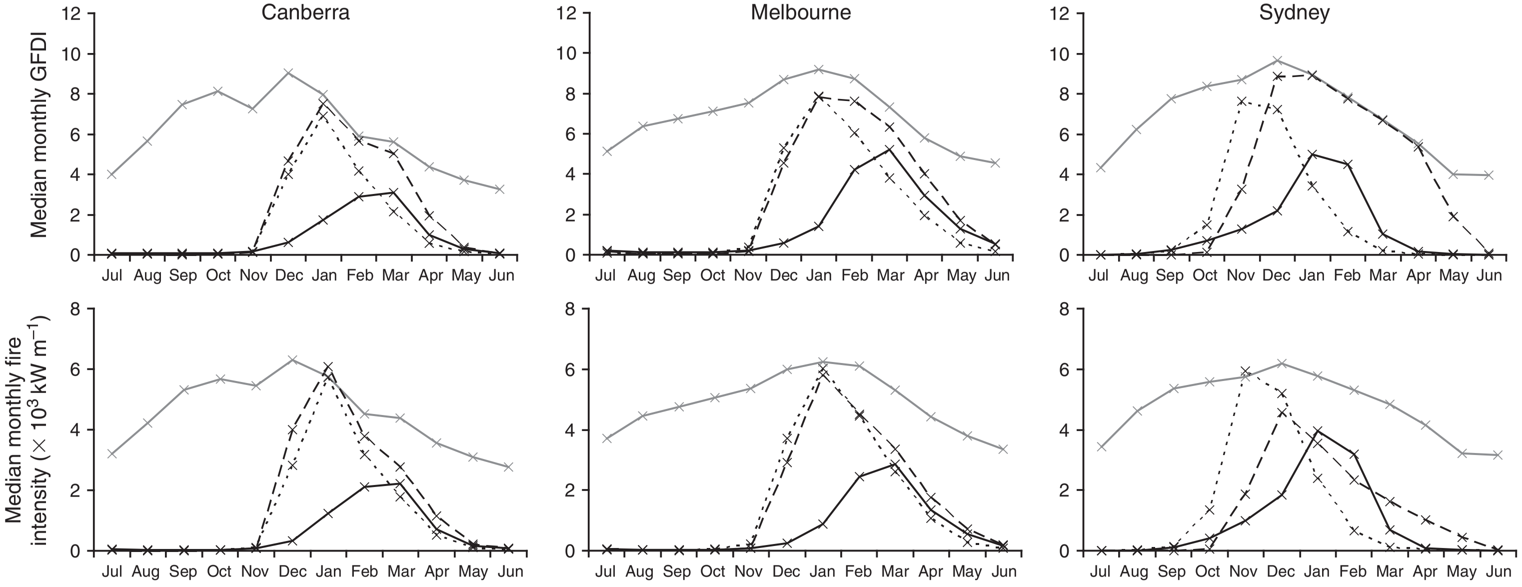

Fig. 2. Historical, monthly median Grassland Fire Danger Index (GFDI) and potential fire-line intensity calculated from either constant curing and fuel variables (100% curing; 4.5 t ha^{-1} fuel load) (grey solid line) or variable GRAZPLAN-derived curing and fuel load (native perennial grasslands, black solid line; exotic perennial grasslands, black dashed line; exotic annual grasslands, black dotted line).

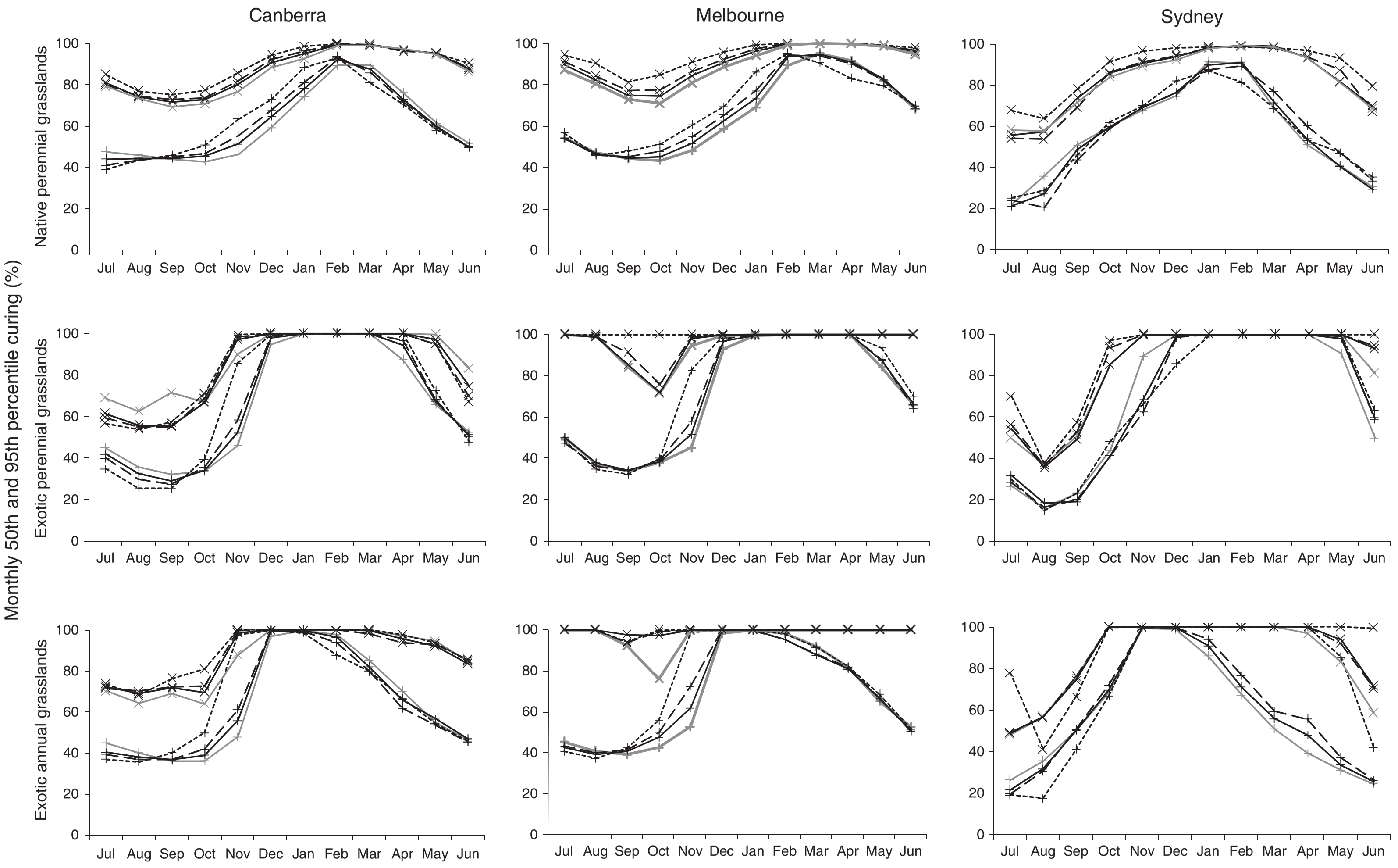

Fig. 3. Monthly 50th (+) and 95th (×) percentile curing values for three locations (Canberra, Melbourne, Sydney), three grassland types and for all climates (historical, grey solid line; 2030 A1B, black solid line; 2070 B1, black dashed line; 2070 A1FI, black dotted line).

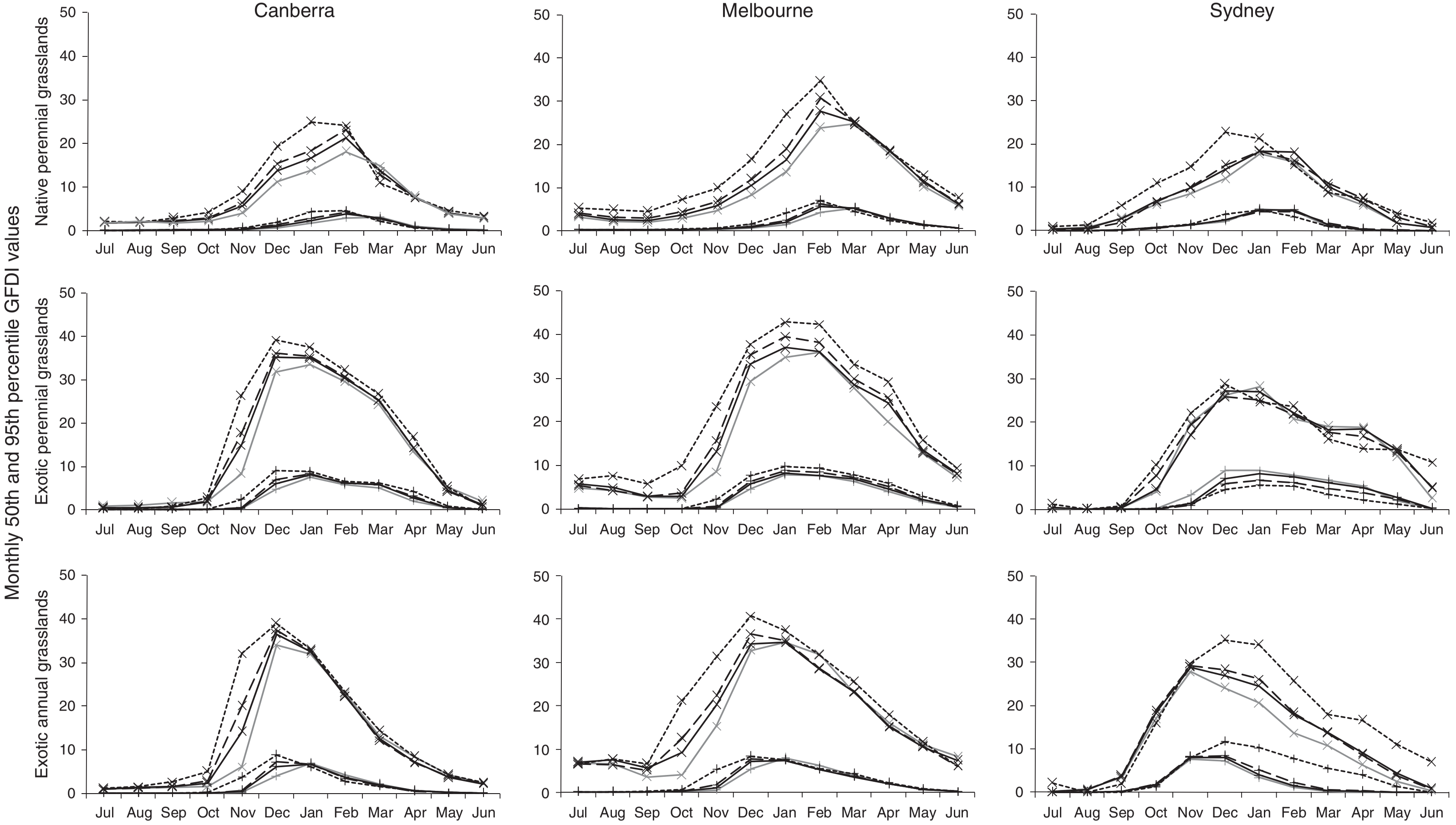

Fig. 4. Monthly 50th (+) and 95th (×) percentile Grassland Fire Danger Index (GFDI) values for three locations (Canberra, Melbourne, Sydney), three grassland types and for all climates (historical, grey solid line; 2030 A1B, black solid line; 2070 B1, black dashed line; 2070 A1FI, black dotted line).

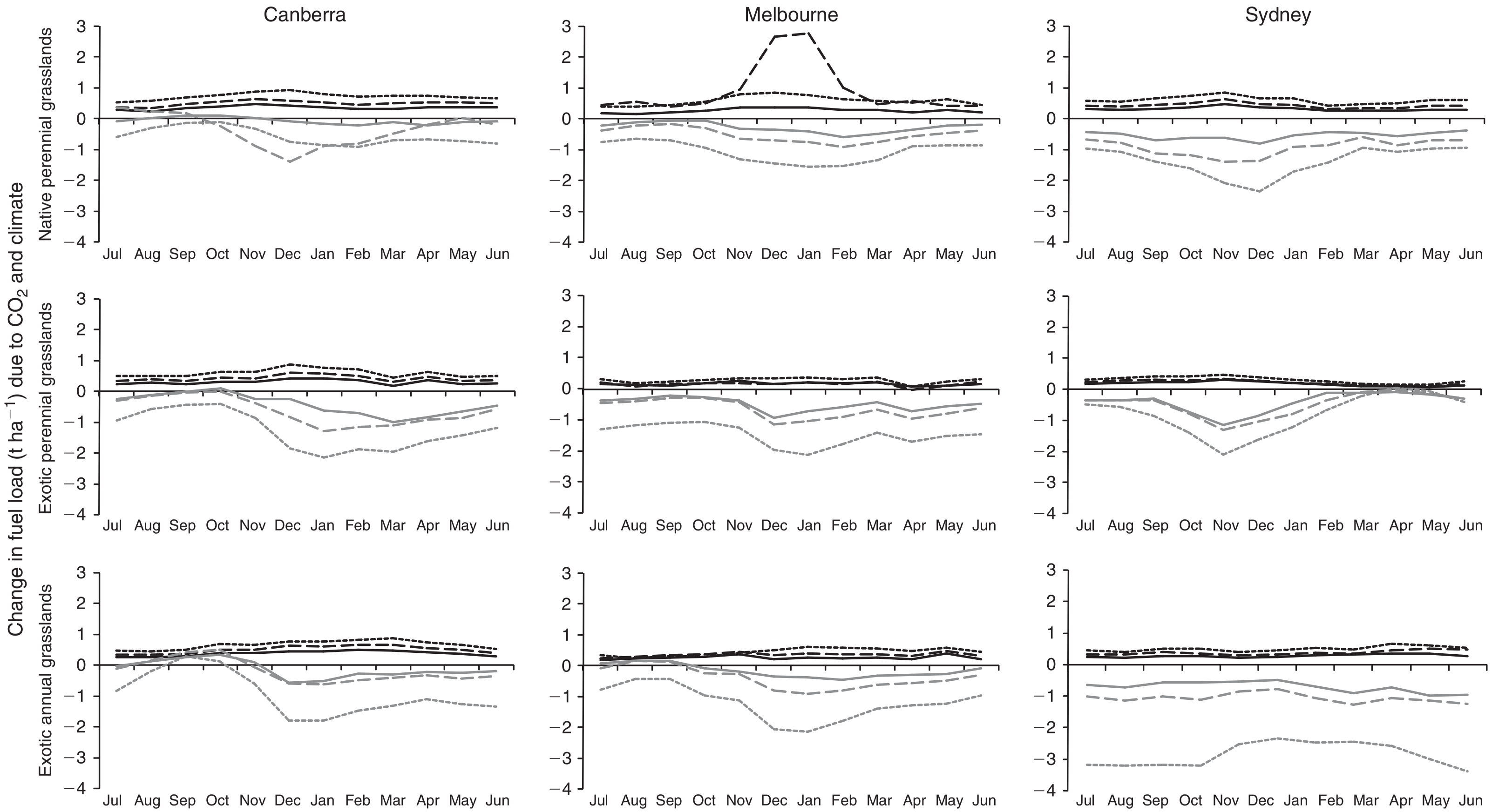

Fig. 5. Direct effect of CO_2 fertilisation (black lines) and the indirect effect of changing temperature and rainfall (grey lines) on the 50th percentile fuel load for projected climates (2030 A1B, solid lines; 2070 B1, dashed lines; 2070 A1FI, dotted lines), grasslands and locations.

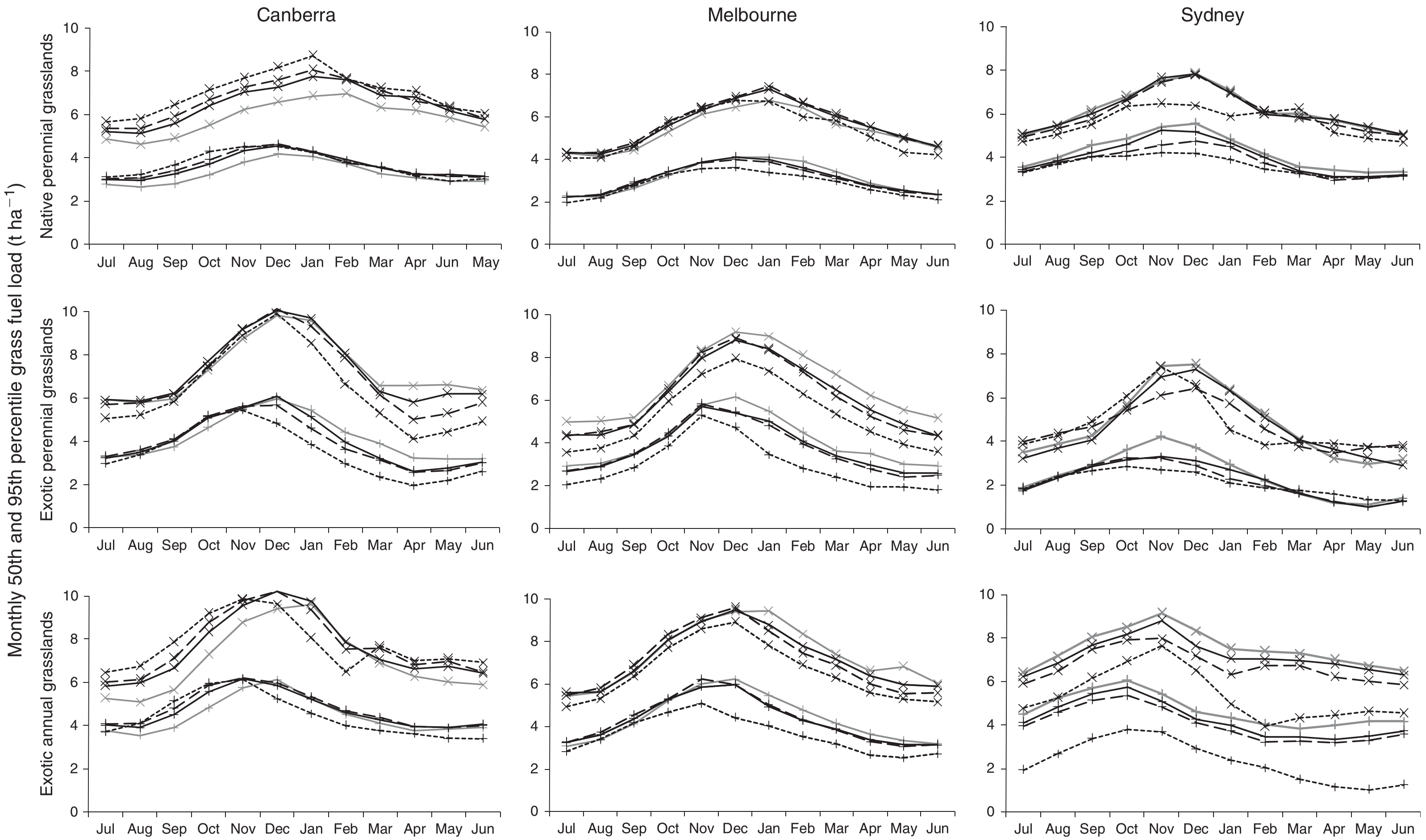

Fig. 6. Monthly 50th (+) and 95th (×) percentile monthly grass fuel loads for three locations (Canberra, Melbourne, Sydney), the three grassland types and for all climates (historical, grey solid line; 2030 A1B, black solid line; 2070 B1, black dashed line; 2070 A1FI, black dotted line).

Effects of changing climate and atmospheric CO_2 on potential fire-line intensity

Overall, there was a mixed net effect of future climate and CO_2 combinations on modelled potential fire-line intensity. Higher fire danger, and hence higher spread rate, was variably compensated for by lower fuel loads across the range of modelled grassland types and locations (Fig. 7). For all grasslands at Canberra, and for the native perennial grasslands at Melbourne and Sydney, future climate and atmospheric CO_2 combinations are predicted to be characterised by higher fire-line intensity during spring and early summer (November to January) compared with that predicted for the historical climate and atmospheric CO_2 concentration ($n = 1167$; $KS > KS_{crit} = 0.04$; $\alpha = 0.05$). In contrast, potential fire-line intensity is projected to decline for the exotic perennial and exotic annual grasslands at Sydney for future climate and atmospheric CO_2 combinations ($n = 1167$; $KS > KS_{crit} = 0.04$; $\alpha = 0.05$).

Discussion

Globally, weather, fuel amount and availability, and ignitions interact to strongly influence fire activity (Cheney *et al.* 1993, 1998; Savadogo *et al.* 2007; Archibald *et al.* 2010; Dimitrakopoulos *et al.* 2010; Mulqueeny *et al.* 2011) and our study demonstrates the importance of including realistic representations of weather and fuel dynamics in projections for alternative climate and CO_2 combinations. Regional variations in responses to climate and fuel effects on fire regimes were evident in the current study, demonstrating the importance of including both climate and fuel dynamics in regional fire-regime studies more generally.

Gill *et al.* (2010) demonstrated, for the Canberra region, a large overestimation of monthly GFDI and potential fire-line intensity when calculated with constant values for curing (100%) and fuel load (4.5 t ha^{-1}), relative to daily GRAZPLAN-derived values. This anomaly was also observed in Sydney and Melbourne in the present study, likely indicating a general result for south-eastern Australia and potentially other regions. This has important implications for the interpretation of earlier studies that used one or both of the constant values (e.g. Hennessy *et al.* 2005; Lucas *et al.* 2007; Pitman *et al.* 2007; Sullivan 2010), where although the assumptions were appropriately acknowledged, the implications were not apparent. To present the effect in some perspective, our study demonstrates that differences in GFDI and fire-line intensity arising from using constant maximum curing (100%) and average fuel load (4.5 t ha^{-1}) inputs rather than daily GRAZPLAN-derived curing and fuel dynamics are much larger than differences associated with the climate and CO_2 changes.

The general trend in our study was for curing and GFDI to increase under the influence of warmer, drier future climates. This represents reduced fire-suppression potential and more days on which ignition will likely occur, leading to an increased likelihood of large grassland fires, which will presumably result in shorter interfire intervals. Differences in distributions of GFDI between climate and atmospheric CO_2 combinations, grasslands and locations reflected the timing of climate-driven physiological processes, including temperature and moisture determinants for curing. Changes in atmospheric CO_2 concentration did not significantly affect curing or GFDI. The correlation between warmer, drier climates and GFDI observed here was consistent with earlier south-eastern Australian studies (e.g. Beer *et al.* 1988; Beer and Williams 1995; Williams *et al.* 2001; Cary 2002; Hennessy *et al.* 2005; Lucas *et al.* 2007; Pitman *et al.* 2007), although the climate effect was less in our study that used variable (GRAZPLAN-derived) curing than for earlier grassland studies that used constant (100%) curing.

Modelled fuel loads generally increased with direct effects of elevated levels of atmospheric CO_2, and decreased with indirect effects of warmer, drier climates, resulting in general declines or little change in fuel loads with projected climate and atmospheric CO_2 combinations. Differences in distributions of fuel load between climate and atmospheric CO_2 combinations, grasslands and locations again reflected the timing of climate-driven physiological processes. For most grasslands and locations, future climate and atmospheric CO_2 conditions encouraged earlier spring growth but shortened the growing season, as moisture deficits became exacerbated (increased curing) over the warmer, drier summer and autumn months (December to May) and the phenological cycle of the grasses was accelerated by higher temperatures. This was reflected in the general trend of greatest declines in fuel load between historical and future climates occurring during summer and autumn, and is consistent with empirical observations (e.g. Cullen *et al.* 2009).

In our study, the combined effects of generally higher GFDI and generally lower fuel loads modelled for future climate and atmospheric CO_2 combinations resulted in relatively small changes in modelled future potential fire-line intensity for the majority of grassland types, months and study locations. This is a significant finding compared with earlier studies (e.g. Hennessy *et al.* 2005; Lucas *et al.* 2007; Pitman *et al.* 2007; Sullivan 2010) that focussed on the effects of future climates on fire danger, and did not incorporate expected changes in curing and fuel load arising either directly from changes in atmospheric CO_2 concentrations, or indirectly via changed temperature and precipitation regimes.

In simulations, influences of future changes in atmospheric CO_2 concentration were based on reasoning from physiological principles and literature. Elevated atmospheric CO_2 concentrations improve photosynthetic rates and water-use efficiencies, but net increases have only been predominantly evident in temperate Australian native and exotic grasslands in the absence of increasing temperatures and drying soils (e.g. Lutze and Gifford 1998; Williams *et al.* 2007; Hovenden *et al.* 2008; Howden *et al.* 2008; Cullen *et al.* 2009; Hovenden and Williams 2010; Perring *et al.* 2010). As simulated rainfall was modified for future climates by altering rainfall quantity, rather than the distribution of rain days, there are likely to be differences between simulated and realised soil moisture dynamics and the representation of the extent of dry periods conducive to extreme fire events that have limited suppression potential. Owing to the omission of changes to the distribution of rain days, it is likely that simulated fuel load and curing dynamics may differ somewhat to those realised for future climates. Given the magnitude of the decreases in fuel load and increase in curing observed with climate change in this study, it seems likely that future fuel loads will be lower, and future curing will be higher than or similar to those occurring historically.

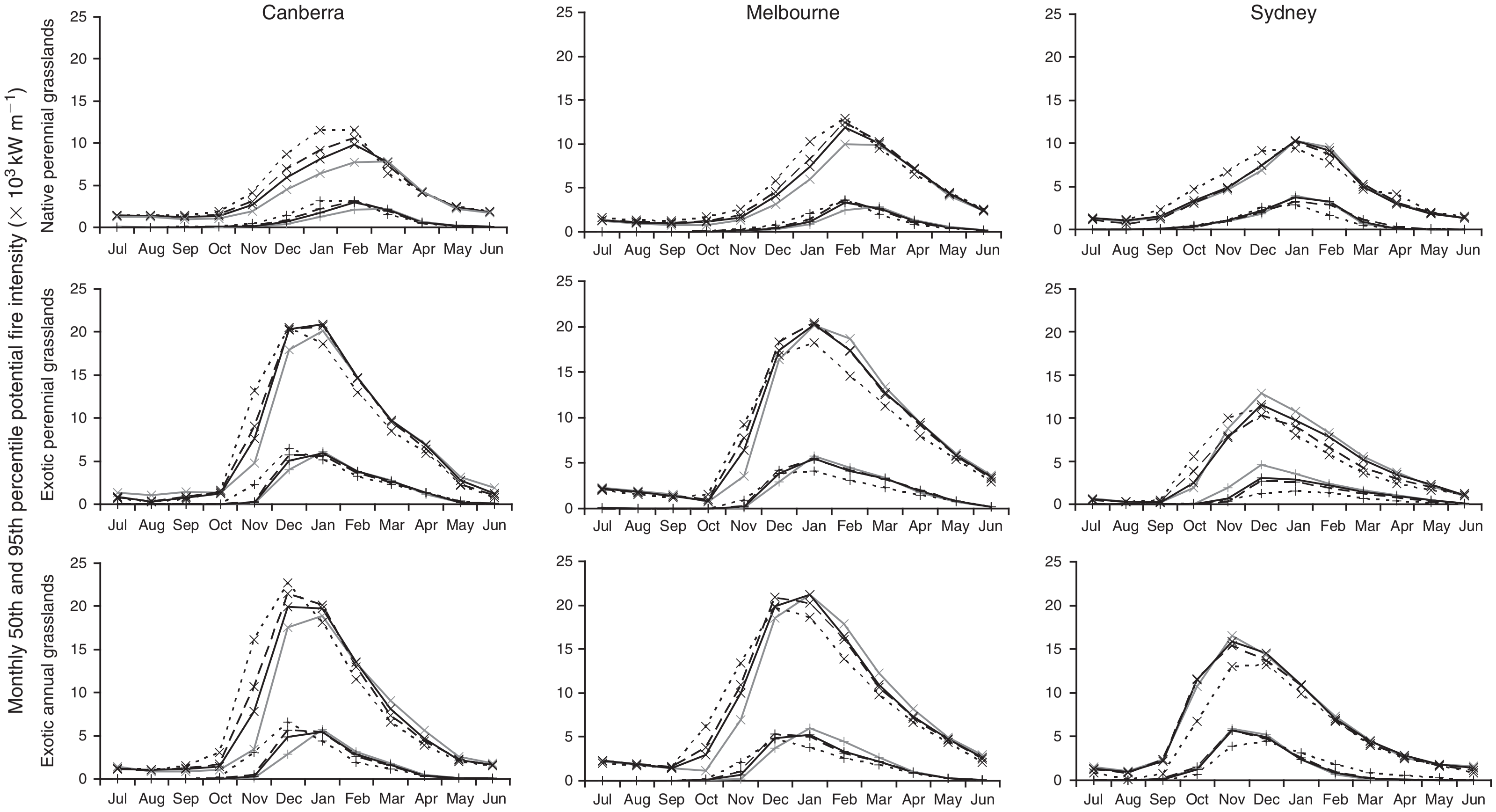

Fig. 7. Monthly 50th (+) and 95th (×) percentile potential fire intensity for three locations (Canberra, Melbourne, Sydney), three grassland types and for all climates (historical, grey solid line; 2030 A1B, black solid line; 2070 B1, black dashed line; 2070 A1FI, black dotted line).

In mixed pastures, which are reasonably common from a global perspective, GFDI and fire-line intensity will reflect the overall curing and fuel load for grassland types present. At each location in this study, differences between distributions of GFDI and potential fire-line intensity were greater between grassland types than between climates. This suggests that climate effects on fire activity could be significantly modified by altering pasture grassland mixes, representing a possible management response to climate change for both conservation and agricultural production. Exploration of the potential of alternative pasture mixes to alter fire activity would be specific to each region studied, and would need to include additional grassland types and herbaceous weeds, and alternative pasture management (e.g. grazing, cutting, irrigation and fertilisation).

Conclusion

This study demonstrates that the net effect of alternative projected future climate and atmospheric CO_2 combinations on fire-line intensity may be minimal because generally increasing grassland fire danger is offset by generally declining fuel loads. Plant growth was directly enhanced by future increases in atmospheric CO_2 concentrations, but this was offset by complex interactions with indirect effects, via temperature and moisture. Further, this finding appears relevant for a range of grassland types and locations in south-eastern Australia, and possibly more generally. Pasture management actions, including altering grassland mixes, grazing, cutting and fertilisation, were not modelled in this study, although these have the potential to markedly alter fire activity.

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