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Climate change effects on pasture systems in south-eastern Australia

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Abstract. Climate change projections for Australia predict increasing temperatures, changes to rainfall patterns, and elevated atmospheric carbon dioxide (CO_2) concentrations. The aims of this study were to predict plant production responses to elevated CO_2 concentrations using the SGS Pasture Model and DairyMod, and then to quantify the effects of climate change scenarios for 2030 and 2070 on predicted pasture growth, species composition, and soil moisture conditions of 5 existing pasture systems in climates ranging from cool temperate to subtropical, relative to a historical baseline. Three future climate scenarios were created for each site by adjusting historical climate data according to temperature and rainfall change projections for 2030, 2070 mid- and 2070 high-emission scenarios, using output from the CSIRO Mark 3 global climate model. In the absence of other climate changes, mean annual pasture production at an elevated CO_2 concentration of 550 ppm was predicted to be 24–29% higher than at 380 ppm CO_2 in temperate (C_3) species-dominant pastures in southern Australia, with lower mean responses in a mixed C_3/C_4 pasture at Barraba in northern New South Wales (17%) and in a C_4 pasture at Mutdapilly in south-eastern Queensland (9%). In the future climate scenarios at the Barraba and Mutdapilly sites in subtropical and subhumid climates, respectively, where climate projections indicated warming of up to 4.4°C, with little change in annual rainfall, modelling predicted increased pasture production and a shift towards C_4 species dominance. In Mediterranean, temperate, and cool temperate climates, climate change projections indicated warming of up to 3.3°C, with annual rainfall reduced by up to 28%. Under future climate scenarios at Wagga Wagga, NSW, and Ellinbank, Victoria, our study predicted increased winter and early spring pasture growth rates, but this was counteracted by a predicted shorter spring growing season, with annual pasture production higher than the baseline under the 2030 climate scenario, but reduced by up to 19% under the 2070 high scenario. In a cool temperate environment at Elliott, Tasmania, annual production was higher than the baseline in all 3 future climate scenarios, but highest in the 2070 mid scenario. At the Wagga Wagga, Ellinbank, and Elliott sites the effect of rainfall declines on pasture production was moderated by a predicted reduction in drainage below the root zone and, at Ellinbank, the use of deeper rooted plant systems was shown to be an effective adaptation to mitigate some of the effect of lower rainfall.

Additional keywords: CO_2 concentration, C_4 species, C_3 species, pasture production, water balance.

Introduction

Climate change projections for Australia indicate increasing temperatures, changes to rainfall patterns, and elevated atmospheric carbon dioxide (CO_2) concentrations (CSIRO and BoM 2007), all of which are likely to affect the productivity of pasture-based systems. The overall effect of future climate changes on pasture production is uncertain and likely to vary regionally, depending on the combination of changes to temperature and rainfall, as well as plant responses to elevated atmospheric CO_2 concentrations (Harle *et al*. 2007; Howden *et al*. 2008; McKeon *et al*. 2009). Temperature projections for Australia predict warming of 0.4–1.8°C by 2030 and 2.2–5°C by 2070 under high-emission scenarios (A1FI storyline, IPCC 2000), with larger increases in inland compared with southern Australia (CSIRO and BoM 2007). There is considerable variation in projected rainfall patterns. The annual rainfall projections for 2030 range from –10 to +5% across northern Australia and from –10% to no change in southern Australia, while under 2070 high-emission scenarios (A1FI), projected changes are for –30 to +20% annual rainfall in northern, central, and eastern Australia, and –30 to +5% annual rainfall across southern Australia (CSIRO and BoM 2007). In southern Australia the rainfall reductions are projected to be largest in winter and spring.

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In addition to changes in temperature and soil moisture, plant production will be influenced by elevated atmospheric CO_2 concentrations through increased photosynthetic and water-use efficiencies (e.g. Ainsworth and Long 2005), resulting in increased biomass production (Long *et al.* 2004; Lüsher *et al.* 2006). The magnitude of the plant production response to elevated CO_2 concentrations will be determined by interactions among pasture type, soil moisture, and soil nutrient availability (Stokes and Ash 2007). Across the Australian rangelands, McKeon *et al.* (2009) demonstrated that elevated CO_2 levels could enhance the positive effect of higher rainfall future climate scenarios on forage production and mitigate the effect of reduced production in lower rainfall scenarios. Howden *et al.* (2008) suggested that increased production from elevated CO_2 would be offset by a 10% rainfall reduction; however, there is a need to evaluate the potential effects of future climate scenarios on Australian grazing systems across a range of regions and pasture types (Harle *et al.* 2007). Biophysical modelling approaches which integrate climatic changes with plant responses to elevated CO_2 concentrations, such as those used in cropping systems (e.g. van Ittersum *et al.* 2003; Anwar *et al.* 2007), are the only means available to do this.

Climate change may also affect grazing systems by altering species composition; for example, warming will favour tropical (C_4) species over temperate (C_3) species (Howden *et al.* 2008). In most cases, C_3 species are of higher forage quality than C_4 species, and are expected to remain so under elevated atmospheric CO_2 conditions (Barbehenn *et al.* 2004), so the effect of climatic change on the balance between C_3 and C_4 species could have important implications for animal production. In addition, changes to rainfall patterns may influence natural resource degradation processes such as erosion and salinity through changes in runoff and drainage patterns (van Ittersum *et al.* 2003; Howden *et al.* 2008).

The objective of this study was to quantify the net effect of future climate scenarios on pasture production systems, using the biophysical grazing systems models DairyMod and the SGS Pasture Model (Johnson *et al.* 2003, 2008). The specific aims were: (*1*) to predict plant production responses to elevated CO_2 concentrations; (*2*) to quantify the net effect of 3 future climate scenarios, based on regional projections for changes to rainfall, temperature, solar radiation, relative humidity, and atmospheric CO_2 concentrations in 2030 and 2070, on the production, species composition, and soil water balance of 5 current pasture systems in eastern Australia; and (*3*) where large reductions in pasture dry matter (DM) production were predicted, to examine if these changes could be mitigated by increasing plant root depth. The pasture systems simulated covered a range of climates from subtropical to cool temperate and pastures that were dominated by C_4 and C_3 species.

Materials and methods

Sites and pasture systems simulations

The effects of future climate scenarios on pastoral systems were modelled at 5 sites in eastern Australia, ranging from a C_4-dominant pasture in subtropical south-eastern Queensland to a C_3 pasture in the cool temperate environment of north-western Tasmania. Site details, including location, climatic zone, and pasture species, are shown in Table 1. All sites were in the medium–high rainfall zone, with the Wagga Wagga site having the lowest mean annual rainfall (565 mm). The SGS Pasture Model and DairyMod version 4.7.5 (Johnson *et al.* 2003, 2008) were used to simulate rainfed (non-irrigated) pasture systems using daily climate data for each site. These models use the same equations for their soil and pasture growth components, and have previously been shown to adequately simulate pasture systems at these and other sites (Cullen *et al.* 2008; Lodge and Johnson 2008). The climate scenarios developed for each site were modelled without nutrient limitation and using a ‘put and take’ grazing system, whereby animal numbers were adjusted daily to maintain pasture mass at 2 tonnes (t) DM/ha and stock were removed when it was less than this value. This system was applied to avoid the use of inappropriate stocking rates across the climate scenarios, which may have otherwise biased the model predictions. The effect of climate scenarios on monthly and annual pasture production, species composition, and the water balance (annual runoff and drainage) at each site was investigated.

Climate scenarios

An historical baseline climate and 3 future climate scenarios were used to compare the effects of climate change on each of the pasture systems. A 30-year climate ‘baseline’ (1971–2000) was used to represent inherent climate variability at each site. Although the period 1961–90 is often used as the baseline for climate change effect analysis, 1971–2000 was adopted as the baseline in this study since it may better reflect recent climate, following the convention of Hennessy (2007). Three future climate scenarios were developed for each site by adjusting

Table 1. Descriptions of each site, including location, soil type (Isbell 1996), climatic zone, mean annual rainfall (1971–2000, mm), and pasture species simulated

Site	Lat., Long.	Soil type	Climate	Rainfall (mm)	Pasture species
Mutdapilly, Qld	–27.63, 152.71	Black Vertosol	Subtropical	859	Rhodes grass (*Chloris gayana*)
Barraba, NSW	–30.55, 150.65	Red Chromosol	Subhumid	661	Native C_3/C_4 perennial grasses
Wagga Wagga, NSW	–35.10, 147.30	Red Chromosol/ Leptic Tenosol	Mediterranean	565	Phalaris (*Phalaris aquatica*), subterranean clover (*Trifolium subterraneum*), native C_4
Ellinbank, Vic.	–38.25, 145.93	Red Mesotrophic Haplic Ferrosol	Temperate	1078	Perennial ryegrass (*Lolim perenne*), white clover (*T. repens*)
Elliott, Tas.	–41.08, 145.77	Red Mesotrophic Haplic Ferrosol	Cool temperate	1220	Perennial ryegrass, white clover

baseline climate data with climate change projections for 2030 and 2070, to create 30-year realisations of each future climate scenario. A 10-year lead-in period, based on 1961–70 historical climate data, was modelled before each scenario to stabilise the initial conditions of the model, but these data were excluded from the analysis.

For each site, historical daily climate data for the 30-year baseline and 10-year lead-in period (i.e. 1 January 1961–31 December 2000) were obtained in April 2008 from the SILO database (www.longpaddock.qld.gov.au/silo/, Jeffrey *et al*. 2001). Patch-point climate datasets were used for Ellinbank, Elliott, and Mutdapilly (Amberley, 15 km north of the site), while interpolated climate data were used at Barraba and Wagga Wagga. Monthly average minimum and maximum temperature and rainfall over the 30-year baseline period were tested for the presence of any linear annual trends (Anwar *et al*. 2007). Few significant trends were observed (as measured by r^2 correlation) and so de-trending of the data was not undertaken. The lack of significant trends may have been related to the relatively short time-frame (i.e. 30 years) for the dataset examined.

The 3 future climate scenarios created for effect analysis were based on a high greenhouse gas emission scenario in 2030, and mid- and high-emission scenarios in 2070 (hereafter referred to as the '2030', '2070 mid', and '2070 high' future climate scenarios). The mid climate change effect scenario was based on the Intergovernmental Panel on Climate Change (IPCC 2000) A1B emission scenario with medium climate sensitivity, while the 2030 and 2070 high scenarios were based on the IPCC (2000) A1FI emission scenario with high climate sensitivity. For each site and future climate scenario, monthly projections for mean temperature (°C) and rainfall (%) change were obtained from the CSIRO Mark 3 global circulation model, via the OzClim database (www.csiro.au/ozclim). The 3 future climate scenarios were selected to represent a range of climate change effects, i.e. temperature increases of 0.7–1.2°C in the 2030, 1.5–2.6°C in the 2070 mid, and 2.5–4.4°C in the 2070 high scenarios, with associated rainfall changes (Table 2). Climate change projections differed for each site, with larger temperature increases and little change in annual rainfall at the northern sites, compared with smaller temperature increases and annual rainfall declines of up to 28% at the southern sites (Table 2). Monthly, rather than annual, temperature and rainfall change projections from the OzClim database were used so that changes to the seasonal pattern could be included in the future scenarios. There was some variability in month-to-month temperature and rainfall projections from the CSIRO Mark 3 model; however, the climatic changes were consistent with the broad projections for Australia, including the seasonal patterns and regional differences (CSIRO and BoM 2007). For example, the changes suggested reduced spring rainfall and increased summer–autumn rainfall at the northern sites, while in southern Australia the majority of the annual rainfall reduction was projected to occur in winter and spring (Fig. 1). Therefore, these temperature and rainfall change scenarios were within the uncertainty bounds of a range of climate models for these sites and were considered appropriate for assessing climate change effect.

Daily historical baseline climate data were scaled according to the climate change projections for each future climate scenario, adapting an approach applied in previous climate change effect analyses (e.g. van Ittersum *et al*. 2003; Anwar *et al*. 2007). To convert rainfall from the historical baseline to scenario rainfall, daily rainfall was multiplied by a factor from OzClim representing the decrease or increase in rainfall for the relevant month and location. For example, to represent a 15% decrease in rainfall, an historical rainfall of 0.2 mm/day was multiplied by 0.85, giving 0.17 mm for the equivalent scenario day. In preliminary analyses, the number of rain days was reduced and larger rainfall amounts increased to represent greater variability of rainfall, but this made little difference to annual pasture growth (unpublished data).

Daily maximum or minimum temperature ($\check{T}$max or $\check{T}$min) for each scenario was calculated from the historical Tmax or Tmin as:

$$\check{T}\text{max} = \text{Tmax} + I_s.f_{s,\text{Tmax}}$$

$$\check{T}\text{min} = \text{Tmin} + I_s.f_{s,\text{Tmin}}$$

where I_s is the increase in mean temperature from OzClim for the relevant month and location, and $f_{s,\text{Tmax}}$ and $f_{s,\text{Tmin}}$ are scalars to represent the relevant change in maximum or minimum temperature. These scalars were read from maps (CSIRO and BoM 2007, fig. 5.10, p. 60) and were in the ranges 1.0–1.15 for maximum temperature and 0.85–1.0 for minimum temperature, indicating that maximum temperature increased more than the minimum temperature. Finally, annual change statistics for radiation (0.7–2.6% increase) and relative humidity (0.6–2.3% decrease) were incorporated for each scenario by applying scalar factors for the changes from the nearest centre reported by CSIRO and BoM (2007, pp. 130–136). Mean monthly rainfall and minimum and maximum temperatures for each site and future climate scenario are presented in Fig. 1.

The baseline scenario used the current ambient atmospheric CO_2 concentration of 380 ppm. This was increased in the 2030 future climate scenario to 455 ppm CO_2, and in the 2070 mid and high scenarios to 581 and 716 ppm CO_2, respectively (IPCC 2000).

Table 2. Annual mean temperature (°C) and rainfall (%) climate change projections for the 2030, 2070 mid, and 2070 high climate scenarios at each site

Site	2030		2070 mid		2070 high	
	Temp.	Rainfall	Temp.	Rainfall	Temp.	Rainfall
Mutdapilly, Qld	1.2	–1	2.6	–3	4.3	–5
Barraba, NSW	1.2	0	2.7	1	4.4	1
Wagga Wagga, NSW	0.7	–8	1.5	–17	2.5	–28
Ellinbank, Vic.	0.9	–6	2	–13	3.3	–22
Elliott, Tas.	0.7	–6	1.5	–13	2.5	–21

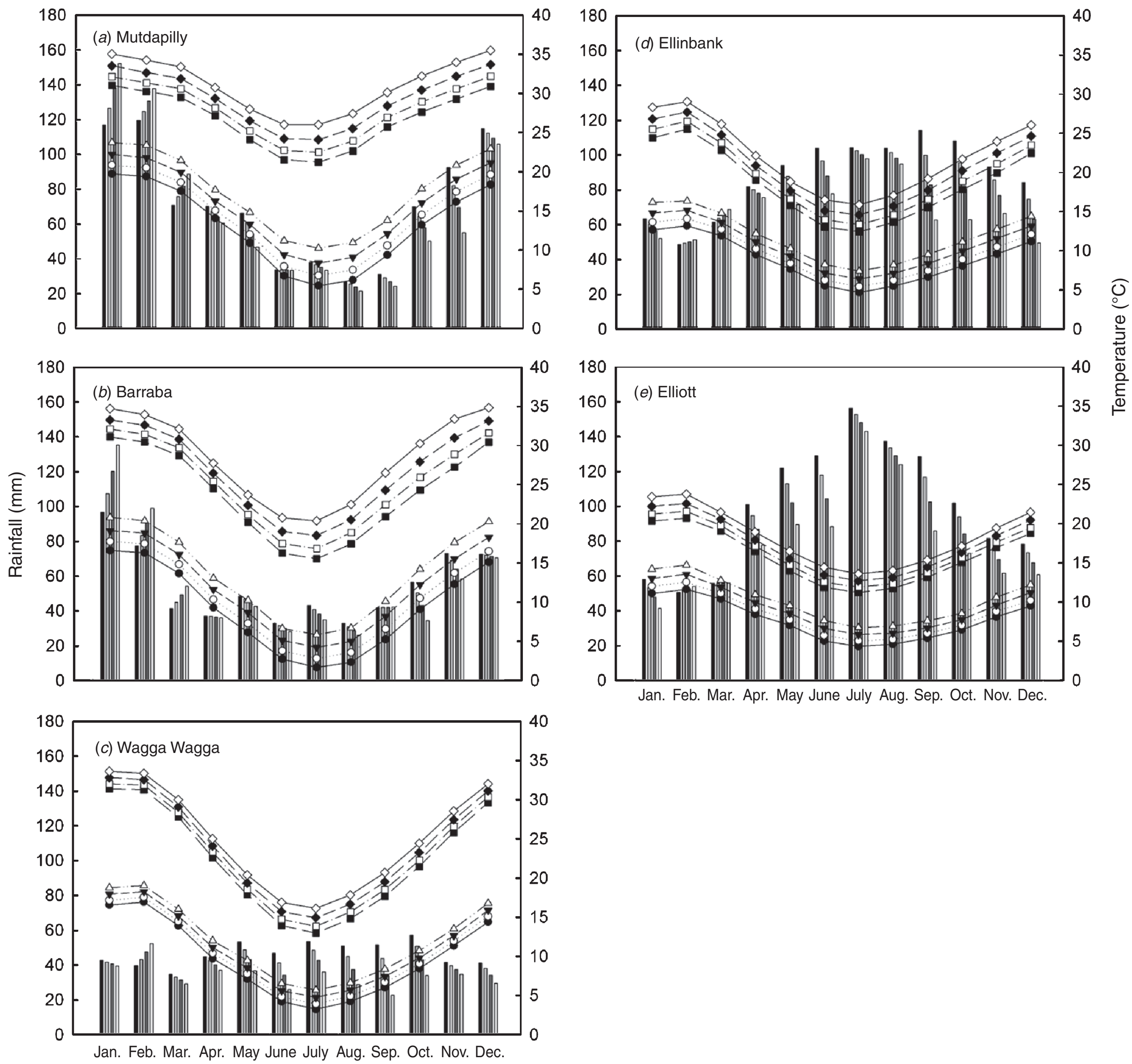

Fig. 1. Mean monthly rainfall (mm) for the baseline (▬), 2030 (▭), 2070 mid (▬), and 2070 high (▭) scenarios; minimum temperature (°C) for the baseline (—●—), 2030 (····○····), 2070 mid (– –▼– –), and 2070 high (–·–△–·–) scenarios; and maximum temperature (°C) for the baseline (– –■– –), 2030 (–·–□–·–), 2070 mid (– –◆– –), and 2070 high (—◇—) scenarios for (*a*) Mutdapilly, Qld; (*b*) Barraba, NSW; (*c*) Wagga Wagga, NSW; (*d*) Ellinbank, Vic.; and (*e*) Elliott, Tas.

Plant responses to elevated CO_2 without other climate changes

Prior to modelling the effects of the 3 future climate scenarios on pasture systems, the annual DM production response to elevated CO_2 concentration was modelled at each site by comparing production at 380 ppm CO_2 (current ambient) with 550 ppm CO_2 in the absence of other changes to climate inputs, using weather data for the baseline scenario (1971–2000). The purpose of these simulations was to demonstrate general agreement between model-predicted DM production responses and measured responses from Free Air CO_2 Enhancement (FACE) studies (Long *et al.* 2004; Ainsworth and Long 2005; Lüsher *et al.* 2006).

The approach used to incorporate plant responses to elevated atmospheric CO_2 concentrations in the SGS Pasture Model and DairyMod is outlined in Appendix 1. In the current study, model responses for leaf photosynthetic potential, plant N content, and canopy conductance were parameterised at 550 ppm CO_2 in accordance with experimental results from FACE studies (Table 3). While some care must be taken in directly comparing model responses with experimental results, because the responses measured are relative to different baseline and

Table 3. Comparison of model responses for C_3 and C_4 species to elevated CO_2 (550 ppm *v.* a baseline of 380 ppm) for leaf photosynthetic potential, plant nitrogen (N) concentration, and canopy conductance with results from FACE studies where a similar degree of CO_2 elevation was used

Plant trait	Model response	FACE experimental response
Leaf photosynthetic potential	C_3: 25%	30–40% (Ainsworth and Long 2005); grasses 30–42, crops 10–22% (Long *et al*. 2004)
	C_4: 10%	2–20% (Ainsworth and Long 2005); grasses –12 to 10, crops 7–32% (Long *et al*. 2004)
Plant N content	C_3: –11%	–10 to –18% (Long *et al*. 2004; Ainsworth and Long 2005); –3 to –10 (Barbehenn *et al*. 2004)[A]
	C_4: –6%	–10 to –18% (Long *et al*. 2004; Ainsworth and Long 2005); 0 to –8 (Barbehenn *et al*. 2004)[A]
Canopy conductance	C_3/C_4: –21%	–10 to –35% (Long *et al*. 2004); –18 to –22% (Ainsworth and Long 2005)

[A]Linear interpolation between 370 and 740 ppm CO_2 for individual species mean responses.

elevated CO_2 concentrations, the comparative values in Table 3 demonstrate that the CO_2 effects we used were within the published measured ranges.

Modelling plant adaptation strategies

The effect of increasing the root depth of perennial ryegrass on predicted pasture production under the 2070 high future climate scenario was modelled only at the Ellinbank site. The original root distribution with a maximum root depth of 0.40 m and 50% of roots in the top 0.10 m was compared with a deeper root system, with a maximum root depth of 0.60 m and 50% of roots in the top 0.20 m. Changing root depth had a minimal effect on mean annual root biomass (predicted to be 0.48 and 0.50 t DM/ha, respectively, for the two different root distributions). No other plant characteristics were altered.

Statistical analysis

No formal statistical analysis was applied to the modelled pasture growth and water balance outputs because of inter-correlations in the input climate data and the mechanistic, non-stochastic nature of the models. Trends are presented across the range of future climate scenarios, with the inter-annual variability presented where appropriate.

Results

Predicted production responses to elevated CO_2

An elevated atmospheric CO_2 concentration of 550 ppm in the absence of other climate changes was associated with mean annual pasture production increases of 24–29% on the C_3-dominant pastures at Wagga Wagga, Elliott, and Ellinbank (Table 4). The Mutdapilly pasture had the lowest response (9%), while the mixed C_3/C_4 pasture response at Barraba was intermediate. The range of responses among years was highest at the Mutdapilly and Barraba sites (Table 4).

Climate change effects

Effects of the 2030, 2070 mid, and 2070 high future climate scenarios on predicted pasture production compared with the baseline climate are shown for all sites in Fig. 2. At the Mutdapilly and Barraba sites, the predicted mean annual DM production increased progressively with each future climate scenario, with a tendency for lower simulated spring–early summer growth, but higher pasture growth rates in the other seasons (Fig. 2*a*, *b*). At Mutdapilly, annual average predicted production increased by 3, 10, and 18% over the historical baseline (15.4 t DM/ha) for the 2030, 2070 mid, and 2070 high climate scenarios, respectively. At Barraba the predicted production increases were 16, 41, and 52%, respectively, for the same scenarios over the historical baseline (4 t DM/ha). In the mixed C_3/C_4 pasture at Barraba, there was also a marked change in the seasonal growth pattern of each species, with a contracted C_3 species growing season offset by an increased growing season length and a higher summer growth rate for C_4 species (Fig. 3). There was little effect of the future climate scenarios on annual surface runoff at Mutdapilly, where mean runoff was 66–70 mm for all climate scenarios, and a small increase from 69 mm in the baseline to 90 mm in the 2070 high scenario at Barraba. At Mutdapilly there was no simulated drainage below the root zone, while for Barraba the mean annual drainage was <5 mm for all climate scenarios (data not shown).

At the Wagga Wagga site, mean predicted annual pasture production was slightly higher than the baseline (7.0 t DM/ha) under the 2030 and 2070 mid scenarios (5 and 1%, respectively), but declined by 18% under the 2070 high scenario (Fig. 2*c*). The simulated future climate scenarios at Wagga Wagga indicated that higher pasture growth rates in winter and early spring were expected with a progressive shortening of the spring growing season (Fig. 2*c*). A similar change to the seasonal pasture growth pattern was observed in the temperate environment at Ellinbank, with a 4% increase in mean annual pasture DM production

Table 4. Mean annual DM production response (%) to elevated CO_2 (550 ppm *v.* a baseline of 380 ppm) for the baseline climate scenarios (1971–2000) at each site
The annual range of DM responses is shown in parentheses

Site	Pasture species	DM response (%)
Mutdapilly, Qld	Rhodes grass	8.6 (–0.3–15.5)
Barraba, NSW	Native perennial grasses (both C_3 and C_4)	17.1 (1.5–33.8)
Wagga Wagga, NSW	Phalaris, subterranean clover, native C_4 grasses	29.0 (22.5–37.5)
Ellinbank, Vic.	Perennial ryegrass, white clover	23.8 (20.7–28.7)
Elliott, Tas.	Perennial ryegrass, white clover	25.8 (21.9–30.0)

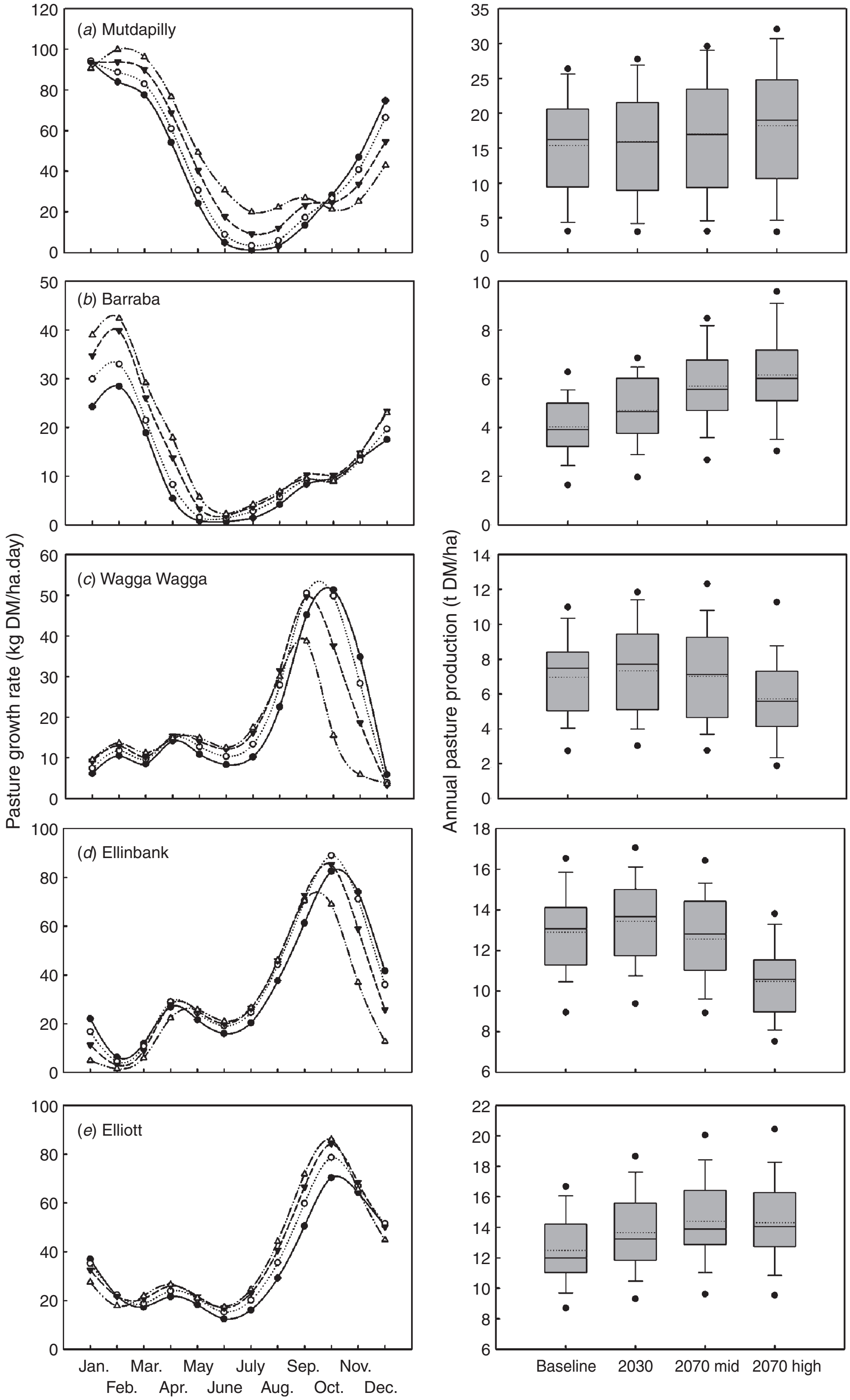

Fig. 2. Mean monthly predicted pasture growth rate (kg DM/ha.day) for baseline (—●—), 2030 (····○····), 2070 mid (– –▼– –), and 2070 high (–·–△–·–) climate scenarios, together with box-plots (5th, 10th, 25th, 50th, 75th, 90th, and 95th percentile, with dotted mean line) of predicted annual production (t DM/ha) for the baseline, 2030, 2070 mid, and 2070 high climate scenarios at (*a*) Mutdapilly, Qld; (*b*) Barraba, NSW; (*c*) Wagga Wagga, NSW; (*d*) Ellinbank, Vic.; and (*e*) Elliott, Tas.

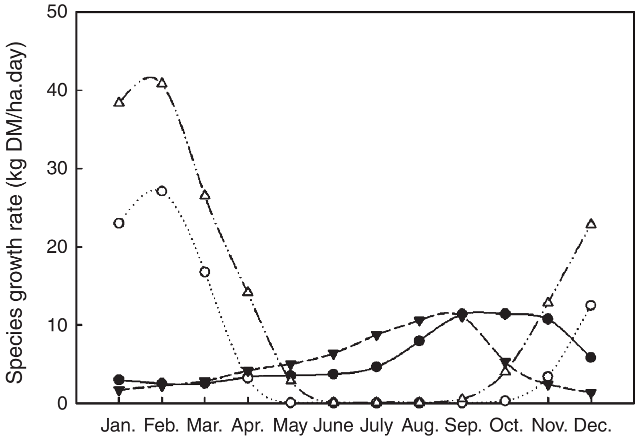

Fig. 3. Mean monthly C_3 and C_4 species predicted growth rates (kg DM/ha.day) at Barraba, NSW, for the baseline (C_3 —●—, C_4 ····○····) and 2070 high (C_3 – –▼– –, C_4 –·–△–·–) climate scenarios.

in the 2030 scenario compared with the baseline (12.9 t DM/ha), but declines of 3 and 19% under the 2070 mid and 2070 high scenarios, respectively (Fig. 2*d*). At Elliott, predicted annual pasture production was higher than the baseline (12.5 t DM/ha) under all 3 future climate scenarios, but the increase was highest under the 2070 mid scenario (15%), compared with 10% in the 2030 and 14% in the 2070 high scenarios (Fig. 2*e*). At all of the southern sites, no predicted runoff occurred for the simulations (data not shown) and drainage was reduced under the future climate scenarios (Fig. 4).

Adaptation strategy

The adaptation strategy of increasing root depth from 0.40 to 0.60 m at Ellinbank in the 2070 high climate scenario increased predicted length of the spring growing season and the peak spring growth rate by 10 kg DM/ha (Fig. 5). Mean predicted total annual pasture production increased from 10.5 to 11.6 t DM/ha, but was less than the baseline simulation (12.9 t DM/ha). With the deeper

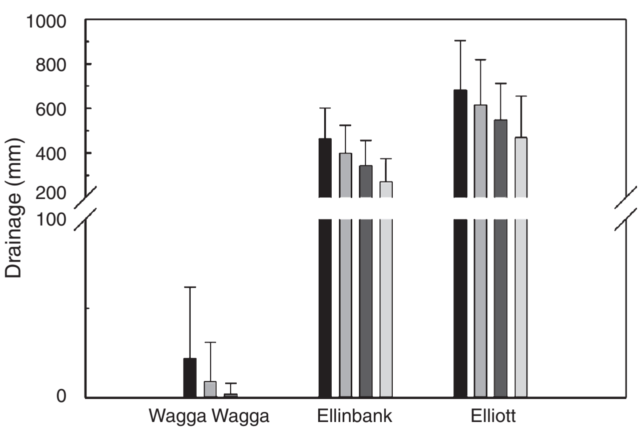

Fig. 4. Predicted mean annual drainage (mm/year) at the Wagga Wagga, NSW, Ellinbank, Vic., and Elliott, Tas., sites for the baseline (▬), 2030 (▬), 2070 mid (▬), and 2070 high (▭) climate scenarios. Error bars indicate one standard deviation.

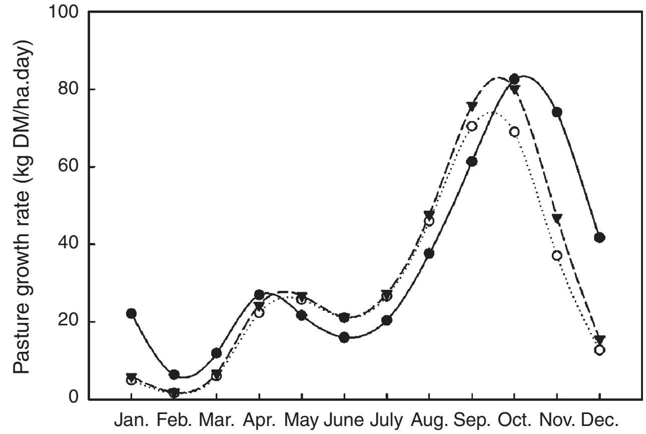

Fig. 5. Effect of increasing root depth from 0.40 (····○····) to 0.60 (– –▼– –) m on the mean monthly pattern of predicted pasture growth rate (kg DM/ha.day) in the 2070 high climate scenario at Ellinbank, Vic. The pasture growth rates for 0.40 m root depth in the baseline climate scenario (—●—) are also shown for comparison.

root system, the predicted mean annual drainage was reduced from 270 to 252 mm.

Discussion

The expected effect of future climate scenarios on pasture production of 5 systems across south-eastern Australia was determined by modelling how existing well adapted pasture species at each site responded to projected increases in temperature, changes in rainfall patterns, and elevated atmospheric CO_2 concentrations. This is the first time that such a comprehensive analysis has been undertaken for a range of sites and pasture types in this region.

Predicted production responses to elevated CO_2

The magnitude of the predicted DM production response simulated by raising the atmospheric CO_2 concentration from 380 to 550 ppm was dependent on site and pasture system, with the largest increases (22–37%) generally occurring in the C_3-dominant pastures in southern Australia and the smallest responses in the C_4 pasture at Mutdapilly, in south-eastern Queensland (0–15%, Table 4). These modelled production increases are consistent with comparable results from FACE experiments, particularly where soil nutrients were non-limiting. For example, Lüsher *et al*. (2006) measured a 7–32% increase in annual DM production at 600 ppm CO_2 in an nitrogen (N) fertilised, mixed perennial ryegrass/white clover pasture in Switzerland, with the higher responses recorded at higher levels of soil fertility. Similarly, Long *et al*. (2004) reported DM increases of 17–22% and –2 to 12% for C_3 and C_4 species, respectively. Comparable results were also reported by Ainsworth and Long (2005). In our study, the production increases simulated at 550 ppm CO_2 were higher than the biomass multipliers used in crop models such as DSSAT-CERES and EPIC/CropSyst [i.e. 11–19% for C_3 species and 4–8% for C_4 species (Tubiello *et al*. 2007)], but the magnitude of the difference between responses for C_3 and C_4 species was similar. The CO_2 responses modelled in our study were under non-limiting soil nutrient conditions; however, lower responses would be expected when other factors such as soil N availability are limiting (Lüsher *et al*. 2006; Newton *et al*. 2006).

Responses to climate change scenarios

The net effect of future climate scenarios on predicted pasture production was determined by increased plant production under elevated CO_2 concentrations, together with responses to higher temperatures and changed rainfall patterns. Howden *et al*. (2008) suggested that increased plant production from higher CO_2 concentrations would be counteracted by a rainfall reduction of ~10%. Our study confirmed this finding for the Mediterranean and temperate climates at Wagga Wagga and Ellinbank, since there was either little change or small increases in simulated annual pasture production when rainfall decreased by up to 10% (i.e. the 2030 and 2070 mid scenarios), but reduced pasture production with larger rainfall reductions (i.e. the 2070 high scenario). However, the modelling for Elliott suggested that this high rainfall, cool temperate environment could cope with larger rainfall declines (>20%) before annual pasture production was reduced. At each of these sites, a change to the seasonal growth pattern was modelled with higher simulated winter and early spring growth rates, reflecting warmer winter temperatures with adequate soil moisture, but the spring growing season was contracted (particularly at Wagga Wagga and Ellinbank, Fig. 2) by higher temperatures and reduced spring rainfall (Fig. 1).

In the subtropical and subhumid climates, increased predicted annual production at the Mutdapilly and Barraba sites appeared to be associated with the heat tolerance of C_4 grasses and the small changes in annual rainfall that occurred for each of the climate scenarios (Fig. 1). At both sites, the C_4 growing season was extended under the warmer climate scenarios, with a reduction in the C_3 growing season at Barraba (Fig. 3), leading to a substantial change in species composition. Since C_3 species are expected to have higher forage quality than C_4 species at elevated CO_2 concentrations, despite some changes in protein and carbohydrate levels (Barbehenn *et al*. 2004), this shift towards C_4 dominance could reduce forage quality, lowering ruminant animal production and increasing methane emissions (Howden *et al*. 2008).

The main predicted effects of future climate scenarios on the water balance were at the southern Australian sites, with a reduction in drainage below the root zone occurring in the drier climate scenarios (Fig. 4). Similar reductions in drainage were modelled under future climate scenarios in wheat cropping systems in Western Australia (van Ittersum *et al*. 2003). With less water entering the watertable there are implications for dryland salinity, nitrate leaching, and streamflow. At the Mutdapilly and Barraba sites, there was little change in predicted surface runoff, but projected increases in rainfall intensity (CSIRO and BoM 2007; Alexander and Arblaster 2009) were not taken into account in these climate scenarios. Higher rainfall intensity events may increase runoff and erosion risk, particularly if they occur in combination with longer dry seasons and lower levels of ground cover (Howden *et al*. 2008).

In dryland pasture systems, deeper rooted perennial plants may have the potential to overcome some of the reduced spring growth by intercepting more of the available water, as shown at the Ellinbank site (Fig. 5). Breeding or selecting for deeper rooted plants could be an effective means of reducing the effect of climate change in southern Victoria. However, it is unlikely that deeper rooted plant systems could increase production in lower rainfall regions where there is historically little drainage (e.g. the Wagga Wagga site, Fig. 4). Other adaptation options, such as improving the heat tolerance of perennial ryegrass, may also need to be evaluated.

In assessing the effects of these future climate scenarios on pasture production, it is important to recognise the limitations of these scenarios and that the climate change projections will most likely change as global circulation models improve in their description of future climatic systems. The method we used to create the future climate scenarios reflected changes to the mean climate, but does not account for projected increases in extreme climate events, such as heat waves and high-intensity rainfall events (CSIRO and BoM 2007; Alexander and Arblaster 2009). Further quantification of these extreme events is required from climate scientists, before their effects on pasture systems can be adequately modelled. It is important also to recognise that the grazing system models we used do not consider plant persistence, so increased temperature or drought effects on plant mortality were not taken into account. However, it is acknowledged that increased plant mortality and the need to re-sow pastures more frequently could have important management and economic consequences. Finally, there are some uncertainties about responses to elevated CO_2; for example, in the Swiss and New Zealand FACE experiments there was evidence of progressive N and phosphorus nutrient limitations developing, and associated increased legume content of pasture (Hartwig and Sadowsky 2006; Newton *et al*. 2006).

Conclusions

While elevated atmospheric CO_2 concentrations alone are likely to increase pasture production, higher temperatures and changes in rainfall patterns will also interact to determine the overall production response under future climate scenarios. In subtropical and subhumid regions of eastern Australia, future climate scenarios indicated warming with little change in annual rainfall, and our study predicted increased pasture production with an extended C_4 species growing season. In southern Australia, where future climate scenarios indicated higher temperatures and reduced rainfall, our study showed that this would lead to only small increases in production in the 2030 scenario, but decreases of up to 19% in the 2070 high scenario. Pasture production was predicted to be more resilient to climate change in the cool temperate environment of northern Tasmania. While these analyses reflected the performance of current pasture systems in future climates, there appeared to be some potential in developing adaptation strategies, such as the use of deeper rooted plants in temperate environments, to mitigate the effects of climate change.

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Appendix 1. Modelling approach used to incorporate carbon dioxide (CO_2) responses

The 3 principal physiological plant responses to elevated CO_2 concentration are:

- an increase in leaf photosynthetic potential;
- a decrease in plant nitrogen (N) content; and
- a decrease in stomatal, and therefore canopy, conductance (Long *et al*. 2004).

While mechanistic approaches are possible to describe these responses (e.g. Johnson *et al*. 1995), simple empirical scaling functions have been used in these whole-system simulation models.

The response of leaf photosynthetic potential, P_{mx} mg CO_2/(m^2 leaf), is defined by:

$$P_{mx} = P_{mx,\mathrm{amb}}\left(\frac{C}{C + K_P}\right)\left(\frac{C_{\mathrm{amb}} + K_P}{C_{\mathrm{amb}}}\right) \tag{1}$$

where C, ppm, is atmospheric CO_2 concentration, C_{amb} is current ambient level, taken to be 380 ppm, K_P, ppm, is a constant, and $P_{mx,\mathrm{amb}}$ is the value of P_{mx} at ambient CO_2. Equation 1 is a simple Michalis-Menten type response, also referred to as a rectangular hyberbola (Thornley and Johnson 2000). The term in the second parentheses is constant and imposes the constraint $P_{mx}(C = C_{\mathrm{amb}}) = P_{mx,\mathrm{amb}}$.

The response of plant N level, f_N, kg N/(kg dry weight), to CO_2 concentrations is described by:

$$f_N = f_{N,\mathrm{amb}}\left[\lambda + (1-\lambda)\frac{(K_N - C_{\mathrm{amb}})^{\alpha}}{(K_N - C_{\mathrm{amb}})^{\alpha} + (C - C_{\mathrm{amb}})^{\alpha}}\right] \tag{2a}$$

where α, is a curvature coefficient, and K_N, ppm, and λ are scaling parameters. According to this equation:

$$f_N(C = C_{\mathrm{amb}}) = f_{N,\mathrm{amb}}$$

$$f_N(C = K_N) = f_{N,\mathrm{amb}}\frac{1+\lambda}{2} \tag{2b}$$

$$f_N(C \to \infty) = \lambda f_{N,\mathrm{amb}}$$

Equation 2*a* confirms that $f_{N,\mathrm{amb}}$ is the value of f_N at ambient CO_2, while Eqn 2*b* shows that, when $C = K_N$, f_N is the average of the value at ambient and saturated CO_2. The third equation in Eqn 2*b* confirms that $f_{N,\mathrm{amb}}$ is reduced by the factor λ at saturated CO_2.

Canopy conductance, which is the sum of leaf stomatal conductances in the canopy, declines in response to CO_2 as described by:

$$g_c = g_{c,mn} + (g_{c,mx} - g_{c,mn})\frac{(1 - g_{c,mm})C_{\mathrm{amb}}^{\beta}}{(g_{c,mx} - 1)C^{\beta} + (1 - g_{c,mn})C_{\mathrm{amb}}^{\beta}} \tag{3a}$$

where β is a curvature coefficient, and $g_{c,mn}$ and $g_{c,mx}$ are values such that:

$$f_g(C = 0) = g_{c,mx}$$

$$f_g(C \to \infty) = g_{c,mn} \tag{3b}$$

$$f_g(C = C_{\mathrm{amb}}) = 1$$

These simple and versatile functions provide flexibility within the model to explore the consequences of different responses to elevated CO_2.