Modelling the resilience of forage crop production to future climate change in the dairy regions of south eastern Australia using APSIM.

K. G. Pembleton[1], B. R. Cullen[2], R. P. Rawnsley[1], M. T. Harrison[1] and T. Ramilan[2]

[1]Tasmanian Institute of Agriculture, University of Tasmania, Private bag 3523, Burnie, TAS 7320, Australia

[2]Faculty of Veterinary and Agricultural Sciences, University of Melbourne, Melbourne, VIC 3010, Australia

Corresponding author: K G Pembleton

Phone: +61 3 6430 4991 Fax: +61 3 6430 4959 Email: Keith.Pembleton@fulbrightmail.org

Running head: Resilience of forage crops to climate change

Modeling the resilience of forage crop production to future climate change in the dairy regions of south eastern Australia using APSIM.

SUMMARY

A warmer and a potentially drier future climate is likely to influence the production of forage crops on dairy farms in the south east dairy regions of Australia. Biophysical modelling was undertaken to explore the resilience of forage production of individual forage crops to scalar increases in temperature, atmospheric CO_2 concentration and changes in daily rainfall. The model APSIM was adapted to reflect species specific responses to growth under elevated atmospheric CO_2 concentrations. It was then used to simulate 40 years of production of forage wheat, oats, annual ryegrass, maize grown for silage, forage sorghum, forage rape and alfalfa grown at three locations in south east Australia with increased temperature scenarios (1, 2, 3 and 4^{o}C of warming) and atmospheric CO_2 concentration (435, 535, 640 and 750 ppm) and decreasing rainfall scenarios (10, 20 or 30% less rainfall). At all locations positive increases in DM yield compared to the baseline climate scenario were predicted for lucerne (2.6 to 93.2% increase), wheat (8.9 to 37.4% increase), oats (6.1 to 35.9% increase) and annual ryegrass (9.7 to 66.7% increase) under all future climate scenarios. The response of forage rape and forage sorghum varied between location and climate change scenario. Without a decrease in rainfall, forage sorghum yield increased at Elliott by between 4.7 and 40.9%. At Dookie forage sorghum yield decreased by between 1.1 and 13.9% under all the future climate scenarios, while at Terang yield decreased by between 0.4 and 16.3% for all senarious except for the 1^{o}C increase in temperature with no change in rainfall. At Elliott and Terang with no change in rainfall forage rape yield increased by between 3.4 and 12.6% up to a 4^{o}C increase in temperature. At Dookie with a decrease in rainfall forage rape yield decreased by between 0.2 and 4.6%. A decrease in forage rape yield at Elliott and Terang only occurred with a 20 and 30% decrease in rainfall. At all locations maize was predicted to have a minimal change in yield under all future climates (between a 2.6% increase and a 6.8% decrease). The future climate scenarios altered the seasonal pattern of forage supply for wheat, oats and lucerne with a increase in forage produced during winter. The resilience of forage crops to climate change indicates that they will continue to be an important component of dairy forage production in south eastern Australia.

Key Words: Forage cropping systems, Dairy production, Biophysical modelling, alfalfa, Forage brassica, Forage corn

INTRODUCTION

The temperate dairy regions of south eastern Australia predominantly utilises pastures comprising of perennial ryegrass (*Lolium perenne* L.) often sown with the perennial legume, white clover (*Trifolium repens* L.) (Fulkerson and Doyle 2001; Read *et al.* 1991). However, many farms strategically use a range of annual and perennial forage crops to supplement the forage supply in periods of low pasture growth or nutritive value (Rawnsley 2007), to better match animal feed demand to forage supply, to improve the productivity on a per land area basis (Garcia *et al.* 2008), or improve resource use efficiency of inputs including water and nitrogen (Garcia *et al.* 2008; Neal *et al.* 2011). More recently there has been interest in fully integrating forage crops into pasture based dairy systems with an aim of improving the productivity and resilience of dairy farms in the face of a changing and variable climate (Chapman *et al.* 2008b; Chapman *et al.* 2011). The most recent survey of feed sources used on Australian dairy farms identified that on average in the south east Australian dairy regions forage crops contribute 19% of the forage component of the milking cows diet (Barlow 2008). Despite the integral role that forage crops have on dairy farms there is a paucity of information on the likely responses of these crops to future changes in climate in south-eastern Australia. Such information will be required by producers, policy makers and the industry as a whole as they attempt to adapt farming systems and practices to become resilient to current and future climatic variability, and more extreme weather events expected in the future.

Future climatic projections for the south eastern dairy regions of Australia generally indicate that the region will become warmer by between 1 and 4^{o}C with either a decrease or no change in annual rainfall (CSIRO and BOM 2007; Holz *et al.* 2010). These projections however, are often uncertain due to the number of different climate models available, a range of possible future greenhouse gas emission scenarios and the large spatial and temporal resolution of the models used for these projections. While methodologies exist to downscale climatic projections to spatial and temporal scales more relevant to agricultural production (Corney *et al.* 2010) and to help identify the most suitable models to use (Smith and Chandler 2010) these methods still produce projections with a large range of variability and uncertainty.

An alternative method of assessing crop production under future climates is to use the range in possible climatic variables within a biophysical modelling frame work to assess the resilience or sensitivity of agricultural production to scaled changes in climatic variables

(Cullen *et al.* 2012). This approach overcomes the uncertainties associated with the use of model-generated future climatic projections while still answering the questions the end user wishes to address (i.e. how resilient is a given production system to future climate change?). Using this method Cullen *et al.* (2012) identified that temperate pastures across south eastern Australia are generally resilient to 1 to 2°C increases in temperature while the response to more extreme changes in climate was dependent on the species composition of the pasture and the location.

The agricultural production system simulator (APSIM) is a crop simulation platform used around the world to assess complex interactions between climate, soils, crops and management (Keating *et al.* 2003). The APSIM framework integrates sub-models describing soil, crop and farm management processes with weather data in a mechanistic manner to simulate crop growth and development as well as soil water and nitrogen dynamics (Keating *et al.* 2003). Through integration with the livestock enterprise modules from the Grazplan and AusFarm models (Freer *et al.* 1997; McCown *et al.* 1993) it is also capable of simulating livestock production within mixed farming systems. The major use of the APSIM framework has to explore long term farming systems questions for broad acre cropping systems (e.g. the grazing vs harvesting of cereal crops (Bell *et al.* 2009), the use of summer crops to prevent recharge into aquifers (Wang *et al.* 2008)). Recently the model has been shown to appropriately represent the factors affecting forage crop growth and development in south eastern Australian regions (Pembleton *et al.* 2013a), and is now being used to explore risks and optimise crop management in intensive forage cropping systems (e.g. Pembleton and Rawnsley 2012; Pembleton *et al.* 2013b). The model also has a framework to represent the nutritive value of forage (Bell *et al.* 2009). Despite popularity over the world there has only been a minimal effort expended to fully parameterise the model to reflect the effect of elevated atmospheric carbon dioxide (CO_2) on crop growth, though studies on maize using APSIM to investigate agricultural production under future climates have shown promising results (Harrison *et al.* 2013). The work of Reyenga *et al.* (1999) using the APSIM wheat module has also shown that such parameterisation is possible and the framework exists in many of the crop modules (Wang *et al.* 2003a).

In the study reported on here, parameters to enable the APSIM crop models to reflect the influence of elevated atmospheric CO_2 concentrations on forage crop production were developed. The APSIM model was then used to examine the resilience of a range of forage crops to projected changes in climate at three locations in the south eastern Australian dairy regions.

MATERIALS AND METHODS

Sites and cropping systems

The locations in south eastern Australia used for this study were Dookie in northern Victoria, Terang in south western Victoria and Elliott in north western Tasmania. These locations were chosen as being representative of the broad climatic conditions that the south eastern Australian dairy regions encompass. The prevailing climatic and edaphic conditions at each location are provided in Table 1.

At each location the growth of forage crops (wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), annual ryegrass (*Lolium multiflorum* Lam.), forage rape (*Brassica napus* L.), sorghum (*Sorghum bicolor* (L.) Moench.), maize (*Zea mays* L.) and lucerne (*Medicago sativa* L.)) was simulated using APSIM (version 7.3) over 40 years using climate data from the years 1971 to 2010 and management rules that were developed in consultation with local agronomists and dairy forage researchers working at the locations simulated (Table 2). Lucerne was simulated as a perennial crop (i.e. sown once at the start of each simulation). For the lucerne simulations, the crop was defoliated when it reached the flowering growth stage irrespective of the time of year. When lucerne was simulated under irrigated conditions, a winter active type was used, while under dryland conditions a winter dormant type was used. This is reflective of the specific adaptation of winter dormant types of lucerne to dryland conditions and the specific adaptation of winter active types of lucerne to irrigated conditions (Pembleton *et al.* 2010a; Pembleton *et al.* 2010b). Irrigation of the irrigated lucerne crops were scheduled using a soil water deficit of 30 mm as the irrigation trigger.

Wheat and oats crops at all locations were simulated with their corresponding crop modules (Wang *et al.* 2003b; Peak *et al.* 2008) under dryland conditions, while maize crops were simulated under irrigation conditions with the maize module (Carberry *et al.* 1989). Lucerne growth was simulated at Elliott and Dookie with the lucerne module (Robertson *et al.* 2002) under both irrigated and dryland conditions at Dookie and Elliott, but only under dryland conditions at Terang. Forage sorghum crops were simulated under dryland conditions at Dookie and Terang and under both irrigated and dryland conditions at Elliott. The canola module (Robertson *et al.* 1999) with the forage rape cultivar described in

Pembleton *et al.* (2013a) was used to simulate the growth of forage rape crops while annual ryegrass crops were simulated with the annual ryegrass ecotype in the weed module (Deen *et al.* 2003). Forage rape growth was simulated under both irrigated and dryland conditions at Dookie and Elliott but only under dryland conditions at Terang. Annual ryegrass was simulated under dryland conditions at all locations. To initialise soil carbon, nitrogen and water conditions, each simulation had a 10 year lead in period in which the growth of a dryland pasture was simulated with the AgPasture module (Li *et al.* 2011) using baseline climate data from the period of 1961 to 1970. The simulation results from this period was not used in any subsequent analysis.

Model modifications

Prior to the commencement of the simulation study, several modifications to the APSIM model were undertaken. These included the addition of parameters to the oat and canola modules to allow them to be grazed by the livestock module and the development of a forage specific cultivar within the canola module. These additions are described in Pembleton *et al.* (2013a). When lucerne growth was simulated, specific manager rules to control the expression of winter dormancy was included as described in Pembleton *et al.* (2011).

Crop and pasture responses to growth under elevated atmospheric CO_2 concentrations

The parameterisation of crop responses (photosynthesis, transpiration efficiency and plant nitrogen content) to growth under elevated atmospheric CO_2 concentration in APSIM has been fully undertaken for wheat (Reyenga *et al.* 1999). However, for the other species used in this study only the influence of elevated atmospheric CO_2 concentration on photosynthesis has been parameterised (see Wang *et al.* (2003a) for details). To develop the crop specific parameters to describe changes to transpiration efficiency and nitrogen concentration for the crops other than wheat, a review of previously published studies investigating the transpiration efficiency and crop nitrogen concentration response of each crop species to growth under elevated CO_2 was undertaken. In this review preference was given to studies investigating the response of swards rather than individual or spaced plants. From the range of responses observed, functions were developed to account for the relative increase/decrease in transpiration efficiency and plant nitrogen concentration against the increase in atmospheric CO_2 concentration. The shape of these functions were chosen based on the functions described by Reyenga *et al.* (1999) for the APSIM wheat module. Tables 3 and 4 presents a summary of the literature review and the modifier functions developed for each crop species. The modifier functions developed were then incorporated into each crop module as for those incorporated for wheat described by Reyenga *et al.* (1999).

To evaluate the validity of the modifier functions that were developed, simulations were undertaken to compare the impact of elevated atmospheric CO_2 on forage crop production without additional changes in temperatures and rainfall to those observed in free air CO_2 enrichment (FACE) experiments containing these crop species (Online supplemental Table 1). The proportional change in dry matter (DM) yield, leaf area index (LAI), tissue nitrogen (N) concentration, transpiration and DM digestibility (DMD) under elevated CO_2 compared to simulations undertaken with ambient CO_2 concentrations was then compared to the proportional change observed in previously published free air CO_2 enrichment (FACE) studies of each crop species or closely related crop species (Online supplemental Table 1). Where no species specific responses have been reported in the literature, the modelled response was compared to the generic responses based on species functional group reported in Ainsworth and Long (2005).

Climatic scaling

Climatic data sets used in this study were obtained as a patched-point datasets in the APSIM file format from the SILO data base (www.longpaddock.qld.gov.au/silo) that has been developed based on the methods described by Jeffrey *et al.* (2001) . This format includes data for daily minimum and maximum temperatures, daily rainfall and daily solar radiation. For each simulation this data was scaled with a 0, 1, 2, 3 or 4^{o}C increase in daily minimum and maximum temperatures (based on the findings reported in CSIRO and BOM (2007)) with corresponding atmospheric CO_2 concentrations of 380, 435, 535, 640 and 750 ppm respectively (creating the scenarios from here on referred to as baseline, T1R0, T2R0, T3R0, T4R0). This was based on the predictions by the Intergovernmental Panel on Climate Change (IPCC 2000). These scenarios were run either with no change in daily rainfall or with a respective 10% decrease in daily rainfall for every 1^{o}C increase in temperature up to a 30% decrease in daily rainfall (creating the scenarios from here on referred to as T1R10, T2R20, T3R30 and T4R30). These changes in temperature and rainfall were selected to be consistent with projections for climate change in southern Australia (CSIRO and BoM 2007). The scaling was applied evenly to all days in the year. Daily solar radiation was not scaled in any of the future climate scenarios.

Simulation outputs and calculations

For each simulation the outputs included grazing yield, silage yield, total biomass yield, and if applicable total irrigation inputs. Dry matter digestibility (DMD) was also an output for the crops modules that had the capacity to simulate that process (wheat and forage sorghum). Grazing yield was calculated as the sum of the growth rate from the date that the crop becomes available for grazing until the crop is terminated or locked up for silage and the forage available for grazing at the start of this period. Silage yields (if applicable) were the crop biomass on the date of the silage harvest. Irrigation input was the sum of the irrigation water applied to the crop from sowing to conclusion.

RESULTS

Response of crops simulated with APSIM to elevated atmospheric CO_2 concentration

The effects of elevated CO_2 on crop biomass, LAI, crop N concentration, transpiration and DMD for the species are presented in Figs 1 to 5. For wheat the simulated biomass, transpiration and LAI response was similar to the response observed in FACE experiments while the crop N concentration and crop DMD modelled responses were within the range reported from FACE experiments (Fig. 1).

The mean simulated change in oat biomass was greater than the accepted response for this crops functional species group. However, the range in modelled responses overlapped this accepted range. The modelled change in oats LAI was within the accepted response range for this crops functional species group. The modelled change in tissue N concentration overlapped the range reported by Ainsworth and Long (2005).

The modelled response of annual ryegrass biomass and LAI to elevated CO_2 was similar to the responses observed in the field under FACE (Fig. 2). For this species there was also an overlap in the modelled values and observed values for crop transpiration and crop N content. This held true across the three locations.

The modelled biomass response for maize was greater than that observed in the field but was within the accepted response range for annual C4 grasses (Ainsworth and Long, 2005). The results of simulations of maize grown at Elliott reflect the observed FACE response for LAI. However, at the other two locations the modelled increase in LAI was greater than that observed under FACE conditions. The simulated change in tissue N concentration for maize crops grown at Elliott and Terang were within the range of responses observed under FACE conditions, while at Dookie this response was within the accepted range for the crops functional species group.

The response of dryland forage rape biomass to elevated CO_2 was similar to that observed under FACE (Fig. 3). The response of the irrigated forage rape was lower than the FACE observations, but was within the range of previously published response for this species. The change in LAI of irrigated forage rape grown at Terang fell within the range observed under FACE conditions while the mean response observed for dryland forage rape at Terang and both dryland and irrigated forage rape at Dookie was above the observed FACE range. However, the range in the modelled response overlapped with the range in observed values. Only the crop N concentration of forage rape grown at Terang and the dryland forage rape grown at Elliott had an overlap between the modelled and accepted response for the plant functional group to which forage rape belongs.

The modelled response to elevated CO_2 of irrigated sorghum biomass was similar to that observed in FACE experiments (Fig. 4). The response of dryland forage sorghum was lower than the FACE observations for this crop species but was within the range of observations for annual C4 grasses. The simulated LAI response to elevated CO_2 of irrigated forage sorghum at Dookie and Terang and dryland forage sorghum at Elliott and Terang aligned with the observations from FACE experiments. For the other irrigation and location combinations the response was within the accepted response range of functional species group this crop belongs to. For the forage sorghum grown at Terang and at Dookie under elevated CO_2 the decrease in tissue N concentration was also within the accepted range defined by Ainsworth and Long (2005) for annual C4 grasses. At Elliott the response was greater than the accepted range. However, the decrease in tissue N concentration was less than this range for the crops grown at Elliott. Similar to the tissue N response the change in transpiration of forage sorghum grown at Dookie and Terang was within the range observed in past FACE experiments. The modelled change in forage DMD with elevated CO_2 was within the range reported for this crop from FACE experiments.

At all locations the simulated change in irrigated lucerne biomass aligned with that observed under FACE conditions (Fig. 5). In contrast, the change in the simulated dryland lucerne biomass was twice that of the response observed in the FACE experiments. However, the range in the response observed for Terang and Elliott overlapped the response observed under FACE. The modelled LAI response of the dryland winter dormant lucerne was above the range for temperate legumes defined by Ainsworth and Long (2005) while the change in LAI for winter active lucerne fell within this range. The range in the predicted response of tissue N concentration of both winter dormant and winter active lucerne overlapped the accepted response range for temperate legumes.

Crop responses to the future climate scenarios

Forage crop yield

The mean simulated yield of each crop grown at each location under the baseline climate scenario is presented in Tables 5 and 6. Under dryland conditions wheat, oats and annual ryegrass had greater yields than forage rape and forage sorghum at all three locations (Table 5). Irrigation improved crop yield of forage rape and lucerne at Dookie and Elliott, and the yield of forage sorghum at Elliott (Table 5 compared to Table 6).

Lucerne and annual ryegrass were the most responsive crops to changes in climate while forage sorghum and forage rape were the least responsive. At all locations wheat, oats, annual ryegrass and lucerne increased in total yield under all future climate scenarios (Table 5). At Elliott, for the T1R0, T2R0, T3R0 and T4R0 scenarios, forage sorghum yield increased above the baseline. Under the same climate scenarios there was no change in forage sorghum yield at Terang and at Dookie the yield of this crop decreased compared to the baseline scenarios. For the T1R10, T2R20, T3R30 and T4R30 scenarios the yield of forage sorghum decreased at all locations. The yield of forage rape grown at Elliott and Terang increased in the T1R0, T2R0, T1R10 and T2R20 scenarios. At Dookie forage rape yield increased in T1R0, T2R0, T3R0 and T4R0 scenarios. However, in the T1R10, T2R20, T3R30 and T4R30 scenarios forage rape yield decreased.

Inter-annual variability in dryland crop yield (as indicated by the CV) at Terang or Dookie remained static or decreased in the T1R0, T2R0, T3R0 and T4R0 scenarios. At Elliott under these conditions, winter dormant lucerne had a decrease in inter-annual yield variability while forage rape had an increase in yield variability. A similar response occurred at Elliott for the T1R10, T2R20, T3R30 and T4R30 scenarios. This response was reversed at

Terang and Dookie. Furthermore at both locations the inter-annual variability in the yield of annual ryegrass increased as rainfall decreased.

As temperatures and atmospheric CO_2 concentrations increased the yield of irrigated forage sorghum and winter active lucerne grown at Elliot and winter active lucerne grown at Dookie increased above the baseline yield (Table 6). At Elliott the yield of irrigated forage rape and maize initially increased above the baseline yields for T1R0 and T2R0 scenarios but then decreased in the T3R0 and T4R0 scenarios. At Dookie the yield of irrigated forage rape was unresponsive to changes in temperature and CO_2 concentration. The yield of maize crops grown at Dookie decreased below the baseline yield in the T1R0, T2R0, T3R0 and T4R0 scenarios. At Elliott the CV in total yield decreased for irrigated forage sorghum and increased for forage rape under the future climate scenarios compared to the baseline scenarios. At Dookie the CV in crop yield of all irrigated crops remained consistent across the future climate scenarios.

Seasonality of forage supply

For both wheat and oats the proportion of yield that was grazed during the winter months increased above the baseline in the future climatic scenarios (Fig. 6). This trend was consistent across all three locations. The proportion of yield that was grazed was slightly lower in the T1R10, T2R20 and T3R30 scenarios compared to the T1R0, T2R0 and T3R0 scenarios.

Spring and summer were consistently the periods with the greatest lucerne growth across all locations, irrigation conditions and climate scenarios (Fig. 7). While small, the proportion of yield of lucerne grown during winter increased as temperatures were increased above the baseline scenarios for lucerne grown under dryland conditions at all three locations and for the lucerne grown under irrigation at Dookie. This increase in winter growth was not observed for the lucerne grown at Elliott under irrigated conditions.

Forage digestibility under future climate scenarios

There was only a very minor influence from the future climate scenarios on the DMD of forage sorghum and wheat. The greatest decrease in forage sorghum digestibility, a 6% decrease in DMD from the baseline scenario, was observed at Elliott under the T4R30 scenario. For forage wheat changes in DMD were small (less than 0.5%).

Changes in irrigation requirements of crop species

Compared to the baseline scenario, at Dookie the irrigation requirement decreased under the future climate scenarios (Table 7) for all crops with the exception of lucerne grown under the T1R10 scenario and the forage rape grown under the T3R30 senario. A similar response was observed for irrigated lucerne grown at Elliott. For forage sorghum and maize grown at Elliott there was an increase in the irrigation requirement for all the future climate scenarios and this increase was greatest for the scenarios that had a decrease in rainfall. For forage rape grown at Elliott the irrigation requirement decreased for the T1R0, T2R0 and T3R0 scenarios. However, for the T1R10, T2R20 and T3R30 scenarios there was an increase in the crops irrigation requirement.

DISCUSSION

Overall the forage crop species examined in this study with the exception of forage sorghum and forage rape showed resilience to potential future changes in climate with either an increase in yield with increasing temperatures and atmospheric CO_2 concentration and either no change or a minimal decrease in DM yield with decreasing rainfall. Forage sorghum yield decreased with a 10% or greater reduction in rainfall while forage rape yield decreased with a 30% decrease in rainfall. Consequently it can be concluded that annual forage crops examined in this study will remain viable forage options for the south eastern Australian dairy regions into the future. However, before this conclusion is accepted the underlying assumptions within the model should be considered. As part of this study, parameters were developed to describe the species specific adaptation to increasing atmospheric CO_2 concentrations, namely the responses of crop transpiration efficiency and crop tissue N concentration. Prior to our modification the model already represented the response of photosynthesis in C3 and C4 plants to increase in atmospheric CO_2 concentrations (Reyenga *et al.* 1999).   An increase in transpiration efficiency in plants exposed to elevated atmospheric CO_2 concentrations occurs as the stomata do not have to open as far for leaf internal CO_2 concentration to be optimum for photosynthesis and hence reduce water loss (Nie *et al.* 1992).   Tissue N concentration decreases with increasing atmospheric CO_2 concentrations due to changes in the balance of the photosynthetic carbon reduction cycle and the photo-respiratory cycle (Conroy and Hocking 1993) and the dilution of N in the additional biomass grown. In APSIM these responses are incorporated into the model through modifier functions for transpiration efficiency and plant N concentration (Reyenga *et al.* 1999; Wang *et al.* 2003a). While it was possible to develop these functions from published data the number and spread of data points for crop transpiration efficiency of annual ryegrass, forage sorghum and oats and tissue N concentration of maize, annual ryegrass and oats was limited. This is a clear gap in the literature and increasing the amount of information relating to the responses of these crops to elevated CO_2 should be a focus of future research effort. Most of the data used to develop the relationships were from atmospheric CO_2 concentrations between 350 ppm and 750 ppm. Consequently model use should be constrained to atmospheric CO_2 concentrations between these values.

A visual assessment of the validity of the modifier functions for transpiration efficiency and plant N concentration modifiers was made by comparing the relative response of crop DM yield, LAI, tissue N concentration and transpiration to elevated atmospheric CO_2 (without changes in other climatic parameters) to the relative response observed in FACE studies. For all the annual crops with the exception of maize and forage rape the response observed in the FACE studies was similar to those predicted by APSIM at each of the locations. Even when there was no data from FACE studies available for comparison, the responses predicted by APSIM were in agreement with the generally accepted responses of plants to elevated atmospheric CO_2 concentrations (Kimball *et al.* 2002; Long *et al.* 2004; Ainsworth and Long 2005). This indicates that the responses of these crops modelled under the future climate scenarios can be taken as legitimate even if the relationships describing these responses were developed using limited data. While the mean maize and forage rape response were outside of those observed in the FACE experiments, the available FACE data for each crop was limited to one growing season and one location. However, the range in most responses of maize crossed the range defined by Ainsworth and Long (2005) for C4 grasses. For dryland forage rape there was better alignment with the observed FACE responses and the defined range for this plants functional group. This reflects the dryland conditions of the FACE experiment and the fact that more data from dryland conditions compared to irrigated conditions was available to Ainsworth and Long (2005) when they defined the expected response range. For lucerne the response predicted for the irrigated crops was similar to that observed in the FACE which was undertaken under dryland conditions (Luscher *et al.* 2000), while the response was over predicted in the dryland simulations. The FACE study in which the response of lucerne growth to elevated CO_2 was determined was undertaken in a high rainfall (1100 mm per year) summer dominant rainfall environment, while the sites used for the simulations have winter dominant rainfall patterns with a range of 567 to 1196 mm in annual rainfall. Potentially a greater response in DM yield to elevated CO_2 concentration for lucerne in the FACE experiment was masked by the availability of water, making this dryland study closer to an irrigated study in terms of the observed response. The transpiration efficiency of legumes is known to be more responsive to changes in atmospheric CO_2 concentration relative to other species (Ainsworth and Long 2005). For forage sorghum and wheat, the response to elevated atmospheric CO_2 concentrations agreed with the observations from FACE experiment. This finding supports the use of APSIM for assessing the impact of elevated atmospheric CO_2 on forage nutritive value as well as forage yield, an important consideration in designing forage cropping systems under future climates where the overall objective is to convert forage into animal product.

A consistent trend across all crops and locations was that the yield response to elevated temperature and atmospheric CO_2 was mediated by a decrease in rainfall. However, the extent of this mediation was dependent on crop type, with the winter grown crops of forage wheat, oats and annual ryegrass having a minimal decrease in yield compared to the summer/spring grown crops of forage rape and forage sorghum. Soil water holding capacity will also impact the resilience summer crops to future decreases in rainfall as there will be a greater reliance on stored soil moisture to support crop growth. There is considerable uncertainty surrounding the magnitude of changes in rainfall in the future climate projections for Australia (CSIRO and BOM 2007). However, if a large decrease in rainfall is received, a shift in dryland forage cropping from summer to winter could be expected.

With the exception of maize and forage sorghum grown at Dookie and Terang, yields of crops increased with an initial increase in temperature and atmospheric CO_2 concentration. This was due to an increase in temperature to those more favourable for crop growth, the fertilisation effect of increasing atmospheric CO_2 concentration on photosynthesis, and for the dryland grown crops, the increase in water use efficiency associated with increasing atmospheric CO_2 concentration (Bunce 2004). However, under the T3R0 and T3R30 scenarios forage rape yield at all three locations and maize yield at Elliott decreased. This response plus the decrease in forage sorghum and maize yield with any increase in temperature above the baseline at Dookie and Terang was potentially due to an increase in the rate of maturity with increase temperatures for these species. Furthermore, the decrease in plant N concentration below that required by the crops for optimum growth with increasing atmospheric CO_2 concentration would have limited growth (Long *et al.* 2004), a response observed in rice (*Oryza sativa* L.) by Makino *et al.* (1997). While an increasing rate of soil N mineralisation may be expected to occur with increasing temperature, the authors have previously identified that in high N input forage cropping systems, soil N has minimal influence on overall yield (Pembleton *et al.* 2013a). Increasing the application of nitrogen fertilisers to these crops under these scenarios could prevent this response (Farage *et al.* 1998) and ensure that the full yield benefits of a CO_2 enriched atmosphere are captured.

The crops with the greatest yield improvements were annual ryegrass and lucerne. The long growing season of annual ryegrass and the year round growth of lucerne meant these crops took the greatest advantage of the improved daily growth rate from increased autumn, winter and spring temperatures and improved water use efficiency associated with the increase in atmospheric CO_2. With climate change similar to the scenarios used in the current study Hatfield *et al.* (2011) suggested a 30% improvement in soybean yield due to an increase in temperature and atmospheric CO_2 concentration. Lucerne was also advantaged by the increase in temperature reducing the time the plant spends in dormancy over winter.

Yield improvements of the annual crops were in line with studies undertaken for other regions with greater yield improvements for C3 crops compared to C4 crops (Hatfield *et al.* 2011). In grain crops, increases in temperature can lead to stress during critical growth stages (e.g. flowering or grain fill) negating the benefits from CO_2 fertilisation and improved WUE (Hatfield *et al.* 2011). However, forage crops that are harvested while still vegetative will avoided these negative consequences of increased temperatures.

Variability, as described by the coefficient of variation, in crop yield decreased or remained stable for the crops investigated with the exception of dryland lucerne and annual ryegrass. Both these crops have a longer growing season compared to the other crops and hence have a greater chance of exposure to water deficits severe enough to counteract the improvements in transpiration efficiency. This is also the reason for the large range in the modelled responses observed for dryland winter dormant lucerne, forage rape, and forage sorghum when CO_2 concentration was increased without additional scaling of temperature and rainfall.

In the forage wheat and oat crops as well as the lucerne crops, the proportion of total yield that was grown and available for grazing during the winter increased as temperature and atmospheric CO_2 concentrations increased for all locations. For lucerne this increase was between 1.8 and 12.3% while for wheat and oats this increase was between 2.2 and 26.8%. The increase in production during winter was due to an extension of the growing season of the crops longer into the cooler months by the by the warmer temperatures. An increase in the proportion of the predicted growth towards winter of perennial pastures in south eastern Australia under future climate scenarios has also been reported (Cullen *et al.* 2008; Cullen *et al.* 2012). While this could help alleviate a common feed deficit on pasture based dairy farms in Australia (Rawnsley *et al.* 2007), the results of Cullen *et al.* (2012) suggested that this will be at the expense of summer pasture growth.

Forage sorghum and wheat DMD changed little from the baseline values under the future climate scenarios. This is in contrast to the predictions for timothy (*Phleum pratense* L.) made by Jing *et al.* (2013) that suggested a decrease in digestibility with future climate change. The longer growing season of perennial pastures increases the periods when the plant is exposed to temperatures high enough to decrease forage digestibility. An analysis of the nutritive value of forage harvested from FACE experiments has also indicated little influence from elevated CO_2 relative to the other experimental factors (i.e. water deficit or stage of harvest) (Akin *et al.* 1994, 1995, Porteaus *et al.* 2009). Based on this simulation analysis and the results of past research, it is likely that there will be minimal change to the digestibility of annual forage crops grown in the southeast Australian dairy regions under future climates.

Irrigation inputs increased for the summer crops grown at Elliott under the future climate scenarios, while at Dookie the irrigation required decreased under the future climate scenarios even with a reduction in rainfall. This was due to a reduced time to harvest maturity (e.g. between 8 and 13 days for wheat) due to warmer growing conditions and the CO_2 driven improvements in transpiration efficiency increase in crop water use efficiency. While this analysis has identified that yield of irrigated forage crops will remain relatively consistent or increase with possible future climate change, the change in the irrigation requirements and the availability of irrigation water to grow such crops (a factor not considered in the current analysis) in the future will determine if they continue to be utilised within dairy systems. Certainly the decrease in irrigation inputs of the irrigated crops grown at Dookie bodes well for the continuation of irrigated forage production in that region.

The approached used in this study was to explore the resilience of forage crops to concurrent increases in temperature and atmospheric CO_2 concentration with or without decreases in rainfall. This approach does not rely on uncertain predictions of future climates while still providing the information industry needs to develop adaptation strategies. Consequently the results of the individual climate scenarios explored should not be interpreted as a definitive forecast; rather it is the trends between the scenarios and the baseline that can be used. The method of climatic scaling used to explore the growth of forage crops under future climates used in this current study fails to take into account the increasing frequency extreme climatic events (e.g. floods and heat waves) that are expected into the future (Alexander and Arblaster 2009). These events will also influence forage crop production, particularly the risks associated with relying on annual forage crops to supply forage within a dairy system (i.e. crop failure). The analysis employed also did not account for the increase in weed growth and increased incidence of pests and diseases that are also predicted to occur under future climates (Hatfield *et al.* 2011). The potential consequences of extreme climatic and biotic events should not be ignored. Furthermore, this study has only considered the resilience of forage crops on an individual basis. Forage crops are often grown within a system to achieve a set of desired outcomes and to address the systems limitations of perennial grass pastures (i.e. improvement in water and nutrient use efficiency, increase production per unit area) (Chapman *et al.* 2008a; Garcia and Fulkerson 2005). Even small changes in the growth and nutritive value of one crop within these systems can have large implications to the forage components within a farms feedbase and the dairy system overall (Rawnsley *et al.* 2013). As such, any consideration of the future role that forage crops will play on dairy farms needs to be evaluated from a systems perspective.

Acknowledgements The authors wish to acknowledge the advice from Dr Joe Jacobs, Dr. Kithsiri Dassanayake, Mr Frank Mickan, Mr Greg O'Brien and Mr Roby Zeissig in the design of the forage crop systems simulated in this study. The authors also acknowledge the Australian Department of Agriculture, Fisheries and Forestry for its financial support for this study.

References

AKIN D. E., KIMBALL B. A., MAUNEY J. R., LAMORTE R. L., HENDREY G. R., LEWIN K., NAGY J., GATES R. N. (1994) Influence of enhanced CO2 concentration and irrigation on sudangrass digestibility. *Agricultural and Forrest Meteorology* **70**, 279-287.

AKIN D. E., KIMBALL B. A., WINDHAM W. R., PINTER P. J., WALL G. W., GARCIA R. L., LAMORTE R. L., MORRISON W. H. (1995) Effect of free-air CO2 enrichment (FACE) on forage quality of wheat. *Animal Feed Science and Technology* **53**, 29-43.

AINSWORTH E. A., LONG S. P. (2005) What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy. *New Phytologist* **165**, 351-371.

ALEXANDER L. V., ARBLASTER J. M. (2009) Assessing trends in observed and modelled climate extremes over Australia in relation to future projections. *Intentional Journal of Climate* **29**, 417-435.

ARANJUELO I., PEREZ P., HERNANDEZ L., IRIGOYEN J. J., ZITA G., MARTINEZ-CARRASCO R., SANCHEZ-DIAZ M. (2005) The response of nodulated alfalfa to water supply, temperature and elevated CO_2: photosynthetic downregulation. *Physiologia Plantarum* **123**, 348-358.

ARANJUELO I., IRIGOYEN J. J., PEREZ P., MARTINEZ-CARRASCO R., SANCHEZ-DIAZ M. (2006) Response of nodulated alfalfa to water supply, temperature and elevated CO_2: productivity and water relations. *Environmental and Experiment Botany* **55**, 130-141.

APSOIL (2010). *APsoil*, Toowoomba: Agricultural Production Systems Research Unit.

BARLOW R. (2008) *National feedbase stocktake report*, Melbourne: Dairy Australia Limited.

BELL L. W., HARGREAVES J. N. G., LAWES R. A., ROBERTSON M. J. (2009) Sacrificial grazing of wheat crops: identifying tactics and opportunities in Western Australia's grainbelt using simulation approaches. *Animal Production Science* **49**, 797-806.

BUNCE J. A. (2004) Carbon dioxide effects on stomatal responses to the environment and water use by crops under field conditions. *Oecologia* **140**, 1-10.

CARBERRY P. S., MUCHOW R. C., MCCOWN R. L. (1989) Testing the CERES-Maize simulation model in a semi-arid tropical environment. *Field Crops Research*. **20**, 297-315.

CHAPMAN D. F., KENNY S. N., BECA D., JOHNSON I. R. (2008a) Pasture and forage crop systems for non-irrigated dairy farms in southern Australia. 1. Physical production and economic performance. *Agricultural Systems* **97**, 108-125.

CHAPMAN D. F., KENNY S. N., BECA D., JOHNSON I. R. (2008b) Pasture and forage crop systems for non-irrigated dairy farms in southern Australia. 2. Inter-annual variation in forage supply, and business risk. *Agricultural Systems* **97**, 126-138.

CHAPMAN D. F., KENNY S. N., LANE N. (2011) Pasture and forage crop systems for non-irrigated dairy farms in southern Australia: 3. Estimated economic value of additional home-grown feed. *Agricultural Systems* **104**, 589-599.

CONLEY M. M., KIMBALL B. A., BROOKS T. J., PINTER P. J. JR., HUNSAKER D. J., WALL G. W., ADAM N. R., LAMORTE R. L., MATTHIAS A. D., THOMPSON T. L., LEAVITT S. W., OTTMAN M. J., COUSINS A. B., TRIGGS J. M. (2001) CO2 enrichment increases water-use efficiency in sorghum. *New Phytologist* **151**, 407-412.

CSIRO, BOM (2007) *Climate change in Australia. Technical Report 2007*. Melbourne: CSIRO Marine and Atmospheric Research.

CHUN J. A., WANG Q. G., TIMLIN D., FLEISHER D., REDDY V. R. (2011) Effect of elevated carbon dioxide and water stress on gas exchange and water use efficiency in corn. *Agricultural and Forest Meteorology* **151**, 378-384.

CONROY J., HOCKING P. J. (1993) Nitrogen nutrition of C3 plants at elevated atmospheric CO2 concentrations. *Physiologia Plantarum* **89**, 570-576.

CULLEN B. R., ECKARD R. J., CALLOW M. N., JOHNSON I. R., CHAPMAN D. F., RAWNSLEY R. P., GARCIA S. C., WHITE T., SNOW V. O. (2008) Simulating pasture growth rates in Australian and New Zealand grazing systems. *Australian Journal of Agricultural Research* **59**, 761-768.

CULLEN B. R., ECKARD R. J., RAWNSLEY R. P. (2012) Resistance of pasture production to projected climate changes in south eastern Australia. *Crop and Pasture Science* **63**, 77-86.

DAEPP M., NOSBERGER J., LUSCHER A. (2001) Nitrogen fertilization and developmental stage alter the response of *Lolium perenne* to elevated CO2. *New Phytologist* **150**, 347-358.

DEEN W., COUSENS R., WARRINGA J., BASTIAANS L., CARBERRY P., REBEL K., RIHA S., MURPHY C., BENJAMIN L. R., CLOUGHLEY C., CUSSANS J., FORCELLA F., HUNT T., JAMIESON P., LINDQUIST J., WANG E. (2003) An evaluation of four crop: weed competition models using a common data set. *Weed Research* **43**, 116-129.

DE LUIS I., IRIGOYEN J. J., SANCHEZ-DIAZ M. (1999) Elevated CO2 enhances plant growth in droughted N2-fixing alfalfa without improving water status. *Physiologia Plantarum* **107**, 84–89.

FARAGE P. K., MCKEE I. F., LONG S. P. (1998) Does a low nitrogen supply necessarily lead to acclimation of photosynthesis to elevated CO2? *Plant Physiology* **118**, 573-580.

FREER M., MOORE A. D., DONNELLY J. R. (1997) GRAZPLAN: decision support systems for Australian grazing enterprises-II. The animal biology model for feed intake, production and reproduction and the GrazFeed DSS. *Agricultural Systems* **54**, 77-126.

FULKERSON B., DOYLE P. (2001) *The Australian Dairy Industry*. Melbourne: Victorian Department of Natural Resources and Environment

GARCIA S. C., FULKERSON W. J. (2005) Opportunities for future Australian dairy systems: a review. *Australian Journal of Experimental Agriculture* **45**, 1041-1055.

GARCIA S. C., FULKERSON W. J., BROOKES S. U. (2008) Dry matter production, nutritive value and efficiency of nutrient utilization of a complementary forage rotation compared to a grass pasture system. *Grass and Forage Science* **63**, 284-300.

HARRISON M. T., TARDIEU F., DONG Z., MESSINA C. D., HAMMER G. L. (2013) Characterizing drought stress and trait influence on maize yield under current and future conditions. *Global Change Biology* **20**, 867–878

HATFIELD J. L., BOOTE K. J., KIMBALL B. A., ZISKA L. H., IZAURRALDE R. C., ORT D., THOMSON A. M., WOLFE D. (2011) Climate Impacts on Agriculture: Implications for Crop Production. *Agronomy Journal* **103**, 351-370.

HOLZ G. K., GROSE M. R., BENNETT J. C., CORNEY S. P., WHITE C. J., PHELAN D., POTTER K., RAWNSLEY R. P., PARSONS D., LISSON S., GAYNOR S. M., BINDOFF N. L. (2010) *Climate Futures for Tasmania: imapcts on agriculture technical report.* Hobart: Antarctic Climate and Ecosystems Cooperative Research Centre.

HUNT M. G., RASMUSSEN S., NEWTON P. C. D., PARSONS A. J., NEWMAN J. A. (2005) Near-term impacts of elevated CO2, nitrogen and fungal endophyte-infection on *Lolium perenne* L. growth, chemical composition and alkaloid production. *Plant Cell Environment* **28**, 1345-1354.

IPCC (2000) *Emissions Scenarios: Special Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

ISBELL R. F. (2002) *The Australian soil classification*. Collingwood: CSIRO Publishing

JEFFREY S. J., CARTER J. O., MOODIE K. M., BESWICK A. R. (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling and Software* **16**, 309-330

JING Q., BELANGER G., QIAN B. D., BARON V. (2013) Timothy Yield and Nutritive Value under Climate Change in Canada. *Agronomy Journal* **105**, 1683-1694.

KEATING B. A., CARBERRY P. S., HAMMER G. L., PROBERT M. E., ROBERTSON M. J., HOLZWORTH D., HUTH N. I., HARGREAVES J. N. G., MEINKE H., HOCHMAN Z., MCLEAN G., VERBURG K., SNOW V., DIMES J. P., SILBURN M., WANG E., BROWN S., BRISTOW K. L., ASSENG S., CHAPMAN S., MCCOWN R. L., FREEBAIRN D. M., SMITH C. J. (2003) An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* **18**, 267-288.

KIM S. H., SICHER R. C., BAE H., GITZ D. C., BAKER J. T., TIMLIN D. J., REDDY V. R. (2006) Canopy photosynthesis, evapotranspiration, leaf nitrogen, and transcription profiles of maize in response to CO2 enrichment. *Global Change Biology* **12**, 588-600.

KIMBALL B. A., KOBAYASHI K., BINDI M. (2002) Responses of agricultural crops to free-air CO2 enrichment. *Advances in Agronomy* **77**, 293-368.

KING K. M., GREER D. H. (1986) Effects of carbon dioxide enrichment and soil water on maize. Agronomy Journal **78**, 515-521.

LI F. Y., SNOW V. O., HOLZWORTH D. P. (2011) Modelling the seasonal and geographical pattern of pasture production in New Zealand. *New Zealand Journal of Agricultural Research* **54**, 331-352.

LONG S. P., AINSWORTH E. A., ROGERS A., ORT D. R. (2004) Rising atmospheric carbon dioxide: plants FACE the future. *Annual Review of Plant Biology* **55**, 591-628.

LUSCHER A., HARTWIG U. A., SUTER D., NOSBERGER J. (2000) Direct evidence that symbiotic N2 fixation in fertile grassland is an important trait for a strong response of plants to elevated atmospheric CO2. *Global Change Biology* **6**, 655-662.

MACDOWELL F. D. H. (1983) Effects of light intensity and CO2 concentration on the kinetics of 1st month growth and nitrogen fixation of alfalfa. *Canadian Journal of Botany* **61**, 731-740.

MAKINO A., HARADA M., SATO T., NAKANO H., MAE T. (1997) Growth and N allocation in rice plants under CO 2 enrichment. *Plant Physiology* **115**, 199-203.

MALMSTROM C. M., FIELD C. B. (1997) Virus-induced differences in the response of oat plants to elevated carbon dioxide. *Plant Cell Environment* **20**, 178-188.

MCCOWN R. L., MOORE A. D., HOLZWORTH D. (1993) APSIM + GrazPlan: versatile software for simulating grain-grazing systems. In *Farming - From Paddock to Plate, Proceedings of the 7th Australian Agronomy Conference*. (Eds GK McDonald, WD Bellotti) Adelaide: Australia.

NEAL J. S., FULKERSON W. J., HACKER R. (2011) Differences in water use efficiency among annual forages used by the dairy industry under optimum and deficit irrigation. *Agricultural Water Management* **98**, 759-774.

NIE D., HE H., KIRKHAM M. B., KANEMASU E. T. (1992) Photosythesis of a C3 and C4 grass under elevated CO2. *Photosynthetica* **26**, 189-198.

PEAKE A., WHITBREAD A., DAVOREN B., BRAUN J., LIMPUS S. (2008) The development of a model in APSIM for the simulation of grazing oats and oaten hay. In *Global Issues, Paddock Action Proceedings of 14th Agronomy Conference,* Adelaide: Australian Society of Agronomy

PEMBLETON K. G., DONAGHY D. J., VOLENEC J. J., SMITH R. S., RAWNSLEY R. P. (2010a) Yield, yield components and shoot morphology of four contrasting alfalfa (*Medicago sativa*) cultivars grown in three cool temperate environments. *Crop and Pasture Science* **61**, 503-511.

PEMBLETON K. G., HARRISON M. T., RAWNSLEY R. P. (2013b) Impact of grazing on the silage yield of forage oat crops. In *Revitalising grasslands to sustain our* *communities: Proceedings of the 22nd International Grassland Congress*. (Eds DL Michalk, GD Millar, WB Badgery, KM Broadfoot) pp. 745-744. New South Wales Department of Primary Industry: Sydney Australia.

PEMBLETON K. G., RAWNSLEY R. P. (2012) Frost risk associated with growing maize for silage on Tasmanian dairy farms. In *Capturing Opportunities and Overcoming Obstacles in Australian Agronomy: Proceedings of 16th Australian Agronomy Conference 2012*. (Ed. I Yunusa). Austalian Society of Agronomy: Armidale, NSW.

PEMBLETON K. G., RAWNSLEY R. P., DONAGHY D. J. (2011) Yield and water-use efficiency of contrasting alfalfa genotypes grown in a cool temperate environment. *Crop and Pasture Science* **62**, 610-623.

PEMBLETON K. G., RAWNSLEY R. P., JACOBS J. L., MICKAN F. J., O'BRIEN G. N., CULLEN B. R., RAMILAN T. (2013a) Evaluating the accuracy of the Agricultural Production Systems Simulator (APSIM) simulating growth, development, and herbage nutritive characteristics of forage crops grown in the south-eastern dairy regions of Australia. *Crop and Pasture Science* **64**, 147-164.

PEMBLETON K. G., SMITH R. S., RAWNSLEY R. P., DONAGHY D. J., HUMPHRIES A. W. (2010b) Genotype by environment interactions of alfalfa (*Medicago sativa* L.) in a cool temperate climate. *Crop and Pasture Science* **61**, 493-502.

PORTEAUS F., HILL J., BALL A. S., PINTER P. J., KIMBALL B. A., WALL G. W., ADAMSEN F. J., HUNSAKER D. J., LAMORTE R. L., LEAVITT S. W., THOMPSON T. L., MATTHIAS A. D., BROOKS T. J., MORRIS C. F. (2009) Effect of Free Air Carbon dioxide Enrichment (FACE) on the chemical composition and nutritive value of wheat grain and straw. *Animal Feed Science and Technology* **149**, 322-332.

PRIOR S. A., TORBERT H. A., RUNION G. B., ROGERS H. H., KIMBALL B. A. (2008) Free-air CO2 enrichment of sorghum: soil carbon and nitrogen dynamics. *Journal of Environmental Quality* **37**, 753-758.

QADERI M. M., KUREPIN L. V., REID D. M. (2006) Growth and physiological responses of canola (*Brassica napus*) to three components of global climate change: temperature, carbon dioxide and drought. *Physiologia Plantarum* **128**, 710-721.

QADERI M. M., REID D. M. (2005) Growth and physiological responses of canola (*Brassica napus*) to UV-B and CO2 under controlled environment conditions. *Physiologia Plantarum* **125**, 247-259.

RABHA B. K., UPRETY D. C. (1998) Effects of elevated CO2 and moisture stress on *Brassica juncea*. *Photosynthetica* **35**, 597-602.

RAWNSLEY R. P. (2007) A review of fodder crops grown in Tasmania, Invited Paper. In *Grasslands Society of Southern Australia 16th Annual Conference, Tasmanian Branch.* (Ed. S. Campbell) pp. 31-37, Launceston: Grasslands Society of Southern Australia

RAWNSLEY R. P., DONAGHY D. J., STEVENS D. R. (2007) What is limiting production and consumption of perennial ryegrass in temperate dairy regions of Australia and New Zealand? In *Dairy Science 2007, Meeting the Challenges for Pasture-Based Dairying, Proceedings of the 3rd Dairy Science Symposium*. (Eds. DF Chapman, DA Clark, KL Macmillan, DP Nation), pp. 256-276, Melbourne: The University of Melbourne

RAWNSLEY R. P., CHAPMAN D. F., JACOBS J. L., GARCIA S. C., CALLOW M. N., EDWARDS G. R., PEMBLETON K. G. (2013) Complementary Forages - integration at a whole farm level. Animal Production Science. **53**, 976-987.

READ J., MCGOWAN T., REED K., WARD G., LOWE K., KAEHNE I. (1991) Perennial Pastures. In *Feedbase 2000: a workshop to determine the priorities for research into soils, pastures and fodder crops in Australian dairy production systems*. (Eds. B Bartsch, W Masons) pp. 35-46, Melbourne: Dairy Research and Development Corporation,

REEVES D. W., ROGERS H. H., PRIOR S. A., WOOD C. W., RUNION G. B. (1994) Elevated atmospheric carbon dioxide effects on sorghum and soybean nutrient status. *Journal of Plant Nutrition* **17**, 1939-1954.

REYENGA P. J., HOWDEN S. M., MEINKE H., MCKEON G. M. (1999) Modelling global change impacts on wheat cropping in south-east Queensland, Australia. *Environmental Modelling and Software* **14**, 297 - 306

ROBERTSON M. J., HOLLAND J. F., KIRKEGAARD J. A., SMITH C. J. (1999) Simulating growth and development of canola in Australia. In *Proceedings of the 10th International Rapeseed Congress*. Canberra, Australia

ROBERTSON M. J., CARBERRY P. S., HUTH N. I., TURPIN J. E., PROBERT M. E., POULTON P. L., BELL M., WRIGHT G. C., YEATES S. J., BRINSMEAD R. B. (2002) Simulation of growth and development of diverse legume species in APSIM. *Australian Journal of Agricultural Research* **53**, 429 - 446.

ROGERS H. H., BINGHAM G. E., CURE J. D., SMITH J. M., SURANO K. A. (1983) Responses of selected plant species to elevated carbon dioxide in the field. *Journal of Environmental Quality* **12**, 569-574.

SCHAPENDONK A., DIJKSTRA P., GROENWOLD J., POT C. S., VANDEGEIJN S. C. (1997) Carbon balance and water use efficiency of frequently cut *Lolium perenne* L. swards at elevated carbon dioxide. *Global Change Biology* **3**, 207-216.

SAGE R. F., SHARKEY T. D., SEEMANN J. R. (1989) Acclimation of photosynthesis to elevated CO2 in five C3 species. *Plant Physiology* **89**, 590-596.

SMITH I., CHANDLER E. (2010) Refining rainfall projections for the Murray Darling Basin of south-east Australia - the effect of sampling model results based on performance. *Climate Change* **102**, 377-393.

TORBERT H. A., PRIOR S. A., ROGERS H. H., RUNION G. B. (2004) Elevated atmospheric CO2 effects on N fertilization in grain sorghum and soybean. *Field Crops Research* **88**, 57-67.

UPRETY D. C., MISHRA R. S., ABROL Y. P. (1995) Effect of elevated CO2 on the photosynthesis, growth and water relation of Brassica species under moisture stress. *Journal of Agronomy and Crop Science* **175**, 231-237.

UPRETY D. C., RABHA B. K. (1999) Effect of elevated CO2 and moisture stress on the carbon and nitrogen contents in *Brassica juncea*. *Biologia Plantarum* **42**, 133-136.

UPRETY D. C., MAHALAXMI V. (2000) Effect of elevated CO2 and nitrogen nutrition on photosynthesis, growth and carbon-nitrogen balance in *Brassica juncea*. *Journal of Agronomy and Crop Science* **184**, 271-276.

WANG E., CRESSWELL H., YU Q., VERBURG K (2008) Summer forage cropping as an effective way to control deep drainage in south-eastern Australia - a simulation study. *Agriculture, Ecosystems & Environment* **125**, 127-136.

WANG E., ROBERTSON M. J., HAMMER G. L., CARBERRY P. S., HOLZWORTH D., MEINKE H., CHAPMAN S. C, HARGREAVES J. N. G., HUTH N. I., MCLEAN G. (2003a) Development of a generic crop model template in the cropping system model APSIM. *European Journal of Agronomy* **18**, 121-140.

WANG E., VAN OOSTEROM E. J., MEINKE H., ASSENG S., ROBERTSON M. J., HUTH N. I., KEATING B. A., PROBERT M. E. (2003b) The new APSIM-Wheat model - performance and future improvements. In *Solutions for a better environment. Proceedings of the 11th Australian Agronomy Conference*. (Eds. M. Unkovich, G. O'Leary) Geelong: Australian Society of Agronomy

WATLING J. R., PRESS M. C., QUICK W. P. (2000) Elevated CO2 induces biochemical and ultrastructural changes in leaves of the C4 cereal sorghum. *Plant Physiology* **123**, 1143-1152.

Online supplementary material caption

Online supplementary table. Online supplementary table 1 provides a summary of the FACE experiment literature used to evaluate the adequacy of the modifier functions within the crop model APSIM.

Table 1. Soil type, drained upper limit (DUL) and lower limit (LL; soil water content at -1500 kpa) in the surface 1200mm of soil at each location and the average daily maximum and minimum temperatures, monthly rainfall and evaporation, during the period of the simulation study (1971 to 2010).

Location	Lat./Lon./Elev.	Soil type[*]	DUL (mm)[†]	LL (mm)[†]	Total annual rainfall (mm)[‡]	Total annual evaporation (US Class A Pan; mm)[‡]	Average monthly maximum and minimum temperatures (°C)[‡]											
							Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Dookie, VIC	36°23'S / 145°41'E/ 189m asl	Vertic calic red chromosol	281.0	121.6	567	1387	29.3	29.1	25.7	20.6	16.1	12.5	11.5	13.1	16.0	19.6	23.8	26.9
							13.9	14.1	11.6	8.0	5.5	3.3	2.5	3.3	4.8	6.9	9.7	11.8
Terang, VIC	38°8'S / 142°35'E/ 136m asl	Brown chromosol	388.0	276.0	733	1294	24.3	24.9	22.8	19.4	16.2	13.5	12.9	13.9	15.5	17.6	20.0	22.3
							11.8	12.3	11.0	9.1	7.5	5.6	5.1	5.6	6.6	7.4	9.0	10.3
Elliott, TAS	41°6'S / 145°48'E/ 208m asl	Red ferrosol	406.8	282.8	1196	1063	20.4	20.8	19.2	16.4	13.9	11.8	11.2	11.7	13.1	14.9	17.1	18.7
							10.9	11.5	10.2	8.3	6.8	5.0	4.2	4.6	5.3	6.3	8.1	9.4

[*] Isbell (2002)
[†] Pembleton *et al.* (2011); APsoil (2010)
[‡] calculated from SILO patched-point data (www.longpaddock.qld.gov.au/silo)

Table 2. Crop agronomic management for the annual forage crops simulated for Dookie and Terang, Victoria and Elliott, Tasmania as part of the study.

Management	Forage wheat	Oats	Annual ryegrass	Forage rape	Forage sorghum	Maize
Sowing	1 Apr to 15 May after 20 mm of rainfall over 3 days	15 Apr to 20 May after 20 mm of rainfall over 3 days	15 Apr to 20 May after 20 mm of rainfall over 3 days	1 Oct	1 Dec	10 Nov
Plant/tiller density (plants or tillers/m^2)	200	200	500	75	50	9
Cultivar	Wedgetail	Taipan	Late	[*]Forage	Sugargraze	Pioneer 3527
Nitrogen fertiliser (kg N/ha)	50 at sowing, 50 following grazing	50 at sowing, 50 following grazing	50 at sowing, 50 following grazing	60 at sowing, 60 at 30 [†]DAS	60 at sowing, 60 at 30 DAS	100 at sowing, 75 at 42 DAS and 75 at 63 DAS
Irrigation management	[‡]NA	NA	NA	If applicable irrigated on a 30 mm [§]SWD	If applicable irrigated on a 30 mm SWD	Irrigated on a 40 mm SWD
Grazing management	Grazed 30 days after reaching a Zadok stage of 25	Grazed 30 days after reaching a Zadok stage of 25	Grazed when biomass > 2800 kgDM/ha to a residual of 1500 kgDM/ha	Grazed when biomass > 3000 kgDM/ha to a residual of 800 kgDM/ha	Grazed when biomass > 3000 kgDM/ha to a residual of 800 kgDM/ha	NA
Silage harvesting/crop termination	harvested for silage when reached a Zadok stage of 45 (booting)	harvested for silage when reached a Zadok stage of 45 (booting)	Grazed and terminated on 31 Oct	Grazed and terminated 45 days after the first grazing or on 1 Mar	Grazed and terminated 45 days after the first grazing or on 31 Mar	Harvested for silage at milk line score of 2.5 (APSIM growth stage of 8.5)

[*] see Pembleton *et al.* (2013) for details

[†] DAS: days after sowing

[‡] NA: not applicable

[§] WD: soil water deficit

Table 3. Published values of the relative increase in crop transpiration efficiency with increases in atmospheric CO_2 concentration and the regressions developed to modify crop transpiration efficiency in APSIM. Functions were developed by fitting regressions to the reported increase in transpiration efficiency to the increase in atmospheric CO_2.

Source	Baseline CO_2 (ppm)	Elevated CO_2 (ppm)	Increase in transpiration efficiency	Function incorporated into APSIM to modify transpiration efficiency
Lucerne				
De Luis *et al.* (1999)	400	700	180%	$y = 0.003x + 1$
De Luis *et al.* (1999)	400	700	80%	
Aranjuelo *et al.* (2006)	395	715	0%	
Maize				
King and Greer (1986)	350	600	32%	$y = 0.0013x + 1$
King and Greer (1986)	350	800	53%	
Rogers *et al.* (1983)	340	520	29%	
Rogers *et al.* (1983)	340	718	60%	
Rogers *et al.* (1983)	340	910	91%	
Chun *et al.* (2011)	400	795	40%	
Forage rape				
Qaderi and Reid (2005)	370	740	73%[*]	$y = 0.0027x + 1$
Qaderi *et al.* (2006)	370	740	62%[*]	
Rabha and Uprety (1998)	350	600	71%[†]	
Uprety *et al.* (1995)	350	600	92%[‡]	
Uprety *et al.* (1995)	350	600	61%[†]	
Uprety *et al.* (1995)	350	600	84%[§]	
Forage sorghum				
Conley *et al.* (2001)	368	561	15%[**]	$y = 0.0008x + 1$
Annual ryegrass				
Schapendonk *et al.* (1997)	350	700	46%[††]	$y = 0.0013x + 1$
Oats				
Malmstrom and Field (1997)	375	725	93%	$y = 0.0027x + 1$

[*] Values for oil seed rape (canola)

[†] Values for *B. juncea*

[‡] Values for *B. nigra*

[§] Values for *B. carinata*

[**] Values for grain sorghum

[††] Values for perennial ryegrass

Table 4. Published values of the relative decrease in plant nitrogen concentration with increases in atmospheric CO_2 concentration and the modifier functions developed from them to modify plant nitrogen concentration in APSIM. Functions were developed by fitting regressions to the reported decrease in plant nitrogen concentration to the increase in atmospheric CO_2.

Source	Baseline CO_2 (ppm)	Elevated CO_2 (ppm)	Decrease in plant nitrogen concentration	Function incorporated into APSIM to modify plant nitrogen concentration
		Lucerne		
Aranjuelo *et al.* (2005)	395	715	20%	$y = 1 \times e^{-0.0008x}$
De Luis *et al.* (1999)	400	700	19%	
MacDowell (1983)	350	720	34%	
		Maize		
Kim *et al.* (2006)	489	745	8%	$y = -0.0003x + 1$
		Forage rape		
Uprety and Mahalaxmi (2000)	350	600	22%[*]	$y = 1 \times e^{-0.0007x}$
Uprety and Rabha (1999)	350	600	29%[*]	
Sage *et al.* (1989)	350	900	25%[†]	
		Forage sorghum		
Watling *et al.* (2000)	350	700	5%[‡]	$y = 1 \times e^{-0.0005x}$
Prior *et al.* (2008)	365	720	32%	
Reeves *et al.* (1994)	357	705	1%	
Torbert *et al.* (2004)	357	750	20%	
		Annual ryegrass		
Hunt *et al.* (2005)	368	446	23%[§]	$y = 1 \times e^{-0.0004x}$
Daepp *et al.* (2001)	350	592	13%[§]	
		Oats		
No studies available				[**]$y = 1 \times e^{-0.0004x}$

[*] Values from *B. juncea*

[†] Values from *B. oleracea*

[‡] Values from grain sorghum

[§] Values from perennial ryegrass

[**] Modifier function derived from the wheat module in APSIM

Table 5. Mean simulated annual yield (tDM/ha) under the baseline climate scenario and the change in the yield relative to the baseline yield of dryland forage crops grown at Elliott Tasmania, Dookie Victoria and Terang Victoria under the future climate scenario of a 1°C, 2°C, 3°C and 4°C increase in temperature and no change in rainfall and a 1, 2, 3 and 4°C increase in temperature with a 10, 20, 30 and 30% respective decrease in rainfall. Increases in air temperatures of 1, 2, 3 and 4^{o}C were associated with atmospheric CO_2 concentrations of 435, 535, 640 and 750 ppm respectively while the baseline scenario had an atmospheric CO_2 concentration of 380 ppm. Values in parenthesis are the coefficients of variation (CV).

Location	Crop	Baseline	+1^{o}C, no change in rain (T1R0)	+2^{o}C, no change in rain (T2R0)	+3^{o}C, no change in rain (T3R0)	+4^{o}C, no change in rain (T4R0)	+1^{o}C, -10% change in rain (T1R-10)	+2^{o}C, -20% change in rain (T2R-20)	+3^{o}C, -30% change in rain (T3R-30)	+4^{o}C, -30% change in rain (T4R-30)
		tDM/ha	% change from the baseline yield							
Elliott Tas	Wheat	6.25 (11.5)	10.2 (11.3)	19.6 (10.0)	26.4 (8.4)	29.9 (7.9)	13.6 (10.2)	26.1 (8.9)	34.8 (6.8)	37.4 (6.0)
	Oats	7.09 (9.6)	8.3 (9.7)	15.5 (10.0)	21.6 (10.4)	25.2 (10.1)	11.4 (8.6)	22.7 (8.3)	32.5 (8.3)	35.9 (7.5)
	Annual ryegrass	6.37 (12.5)	17.9 (12.9)	34.6 (11.2)	52.5 (11.4)	66.7 (9.8)	16.2 (12.6)	30.3 (12.2)	44.0 (10.6)	58.3 (10.4)
	Forage sorghum	4.37 (23.3)	4.7 (24.9)	9.4 (27.0)	11.5 (28.4)	14.0 (30.7)	-0.2 (25.7)	-3.2 (32.3)	-10.6 (39.6)	-8.9 (40.5)
	Forage rape	5.85 (11.2)	4.7 (12.0)	9.7 (11.4)	4.9 (14.4)	-5.52 (14.5)	3.3 (13.5)	6.6 (13.0)	-0.6 (14.8)	-10.7 (15.0)
	Winter dormant lucerne	10.27 (23.4)	21.2 (20.0)	54.1 (17.7)	74.8 (17.0)	93.2 (15.2)	14.6 (21.3)	37.6 (20.6)	46.2 (18.9)	63.5 (17.9)
Terang Vic	Wheat	9.67 (18.0)	9.2 (19.0)	18.0 (19.8)	25.4 (20.2)	32.8 (19.9)	9.7 (19.4)	17.7 (19.8)	20.1 (20.6)	27.2 (20.3)
	Oats	10.11 (10.6)	6.1 (10.5)	12.5 (11.2)	18.4 (10.9)	21.5 (12.3)	7.4 (10.2)	15.1 (10.2)	21.5 (9.3)	22.7 (11.5)
	Annual ryegrass	7.46 (12.2)	12.1 (12.4)	27.7 (11.0)	40.5 (11.1)	51.3 (11.0)	10.9 (12.7)	24.9 (11.6)	30.9 (12.5)	41.4 (13.1)
	Forage sorghum	4.27 (23.7)	1.7 (25.1)	-0.4 (23.2)	-0.4 (22.9)	-0.5 (24.2)	-2.9 (24.9)	-10.0 (27.9)	-16.3 (22.6)	-15.4 (23.9)
	Forage rape	5.52 (15.3)	5.3 (14.6)	12.6 (13.9)	8.2 (16.5)	-2.7 (14.5)	2.0 (15.9)	4.9 (15.3)	-2.1 (17.3)	-9.9 (14.4)
	Winter dormant lucerne	11.42 (16.6)	15.5 (15.8)	39.4 (13.1)	55.0 (11.9)	69.3 (12.4)	8.9 (16.9)	23.4 (15.1)	26.4 (16.9)	42.1 (16.7)
Dookie Vic	Wheat	7.00 (13.1)	8.9 (13.5)	19.2 (13.0)	27.3 (12.9)	33.5 (12.7)	9.5 (13.1)	21.6 (12.1)	27.4 (10.7)	33.5 (10.3)
	Oats	8.21 (13.6)	11.0 (12.5)	19.4 (10.6)	25.1 (11.1)	31.1 (11.4)	11.2 (12.4)	22.4 (9.7)	29.3 (9.6)	35.5 (9.8)
	Annual ryegrass	7.60 (17.0)	12.3 (17.8)	28.2 (15.2)	39.6 (16.3)	52.0 (15.6)	9.7 (19.0)	18.3 (20.0)	16.4 (27.0)	23.8 (28.4)
	Forage sorghum	5.28 (34.5)	-1.1 (34.9)	-1.4 (33.0)	-2.4 (31.2)	-5.2 (30.4)	-4.8 (33.6)	-8.5 (29.7)	-13.0 (25.6)	-13.9 (23.1)
	Forage rape	4.35 (21.8)	2.8 (21.4)	4.6 (20.9)	6.6 (19.3)	7.9 (19.4)	-0.2 (21.6)	-1.3 (20.7)	-4.6 (19.7)	-2.2 (17.7)
	Winter dormant lucerne	10.26 (36.3)	13.4 (37.2)	35.8 (33.9)	55.0 (32.7)	71.9 (31.7)	2.6 (42.0)	7.6 (44.3)	1.9 (52.5)	14.3 (50.4)

Table 6. Mean simulated annual yield (tDM/ha) under the baseline climate scenario and the change in the yield relative to the baseline yield of irrigated forage crops grown at Elliott Tasmania and Dookie Victoria under the future climate scenario of a 1, 2, 3 and 4°C increase in temperature and no change in rainfall. Increases in air temperatures of 1, 2, 3 and 4^{o}C were associated with atmospheric CO_2 concentrations of 435, 535, 640 and 750 ppm respectively while the baseline scenario had an atmospheric CO_2 concentration of 380 ppm. Values in parenthesis are the coefficients of variation (CV).

Location	Crop	Baseline	+1^{o}C, no change in rain (T1R0)	+2^{o}C, no change in rain (T2R0)	+3^{o}C, no change in rain (T3R0)	+4^{o}C, no change in rain (T4R0)
		kgDM/ha	% change from the baseline yield			
Elliott Tas	Maize	26.10 (9.3)	2.6 (2.5)	2.4 (2.3)	0.5 (2.6)	-2.1 (2.8)
	Forage sorghum	6.41 (14.7)	14.7 (10.2)	26.2 (8.4)	35.5 (6.7)	40.9 (4.9)
	Forage rape	6.60 (5.8)	3.4 (6.6)	7.1 (5.9)	5.1 (8.2)	-7.0 (12.9)
	Winter active lucerne	17.56 (8.3)	7.1 (9.2)	13.6 (8.5)	15.5 (8.3)	15.7 (8.8)
Dookie Vic	Maize	25.32 (4.4)	-3.1 (8.9)	-4.6 (7.8)	-5.8 (7.3)	-6.8 (6.8)
	Forage rape	5.61 (2.8)	1.0 (21.4)	2.4 (20.9)	3.2 (19.3)	-0.4 (19.4)
	Winter active lucerne	18.20 (7.4)	9.2 (8.9)	21.1 (9.2)	27.4 (10.3)	28.5 (10.3)

Table 7. The change in irrigation requirement (%) from that of the baseline scenario (mm) of irrigated forage crops grown at Dookie, Victoria and Elliott Tasmania under the +1, +2, +3°C, +1°C with -10% rain, +2°C with -20% rain and +3°C with -30% rain climate scenarios. The baseline, +1, +2 and +3^{o}C scenarios were associated with an atmospheric CO_2 concentrations of 380, 435, 535 and 640 ppm respectively.

	Dookie			Elliott			
Scenario	Lucerne	Forage rape	Maize	Lucerne	Forage sorghum	Forage rape	Maize
	Irrigation requirement (mm)						
Baseline	459	205	563	212	90	60	173
	Change in irrigation requirement relative the baseline (%)						
+1^{o}C, no rain change	-2.3	-4.5	-4.4	-0.9	14.8	-8.6	4.6
+2^{o}C, no rain change	-10.9	-15.5	-10.2	-16.3	19.5	-12.3	5.3
+3^{o}C, no rain change	-20.7	-10.4	-14.3	-21.9	25.3	-10.9	0.8
+1^{o}C, -10% rain	1.1	-2.6	-2.7	4.4	19.2	3.4	10.4
+2^{o}C, -20% rain	-2.1	-5.1	-5.9	-5.2	32.4	0.8	11.4
+3^{o}C, -30% rain	-7.1	3.7	-9.2	-5.2	43.3	14.2	13.9

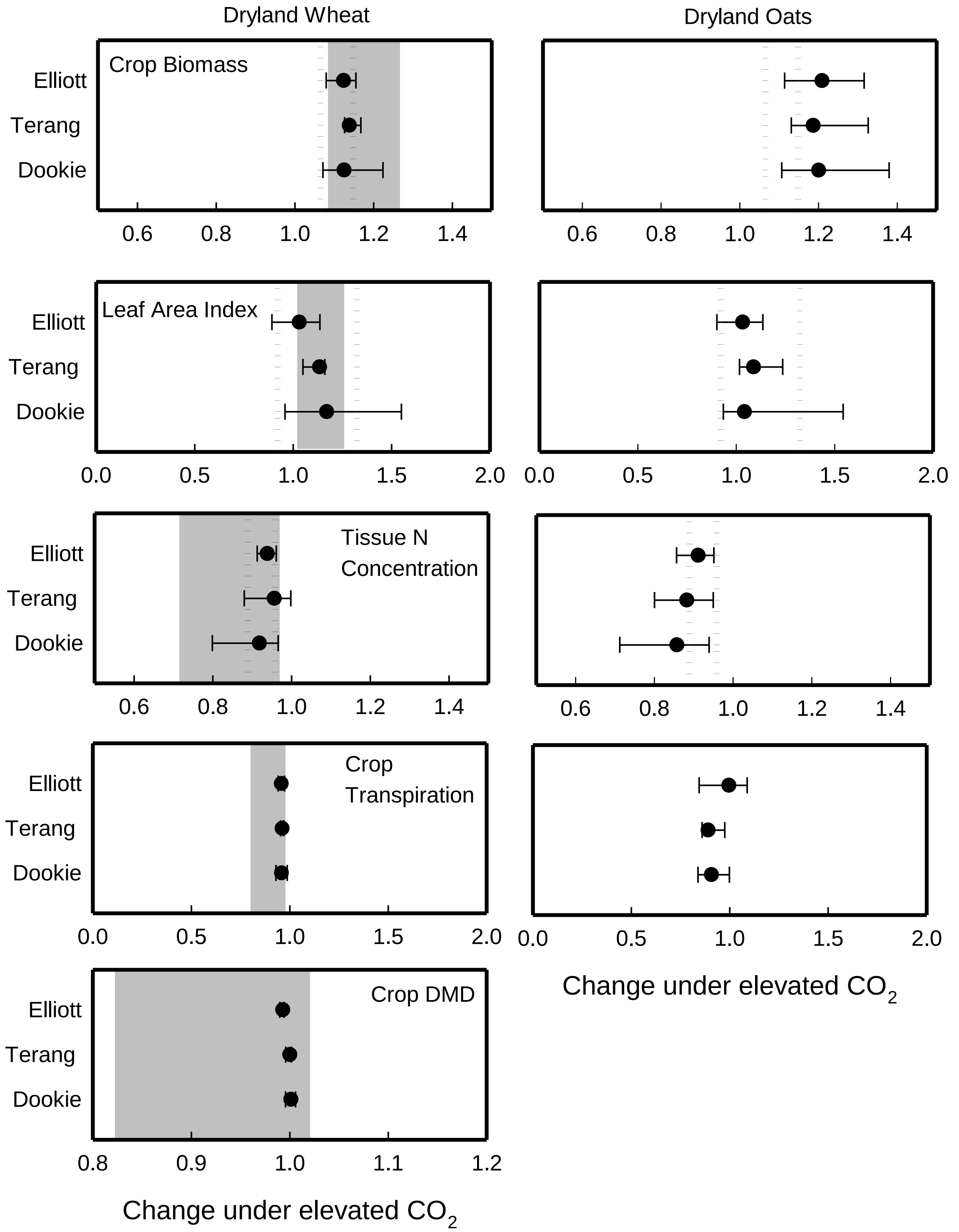

Fig. 1. The mean simulated effect (error bars represent the range in values) of elevated CO_2 (c.a. 600ppm) on crop biomass, leaf area index, tissue nitrogen (N) concentration, crop transpiration and crop dry matter digestibility (DMD) of dryland wheat and oats crops compared to previously published effects observed in FACE experiments as outlined in Online supplemental table 3 (represented by the grey areas) and the effect reported for the most relevant function plant group reported in the meta analysis and literature review undertaken by Ainsworth and Long (2005) (represented by the vertical dotted lines) where

that data was available. An effect less than 1 indicates a decrease while an effect greater than 1 indicates an increase.

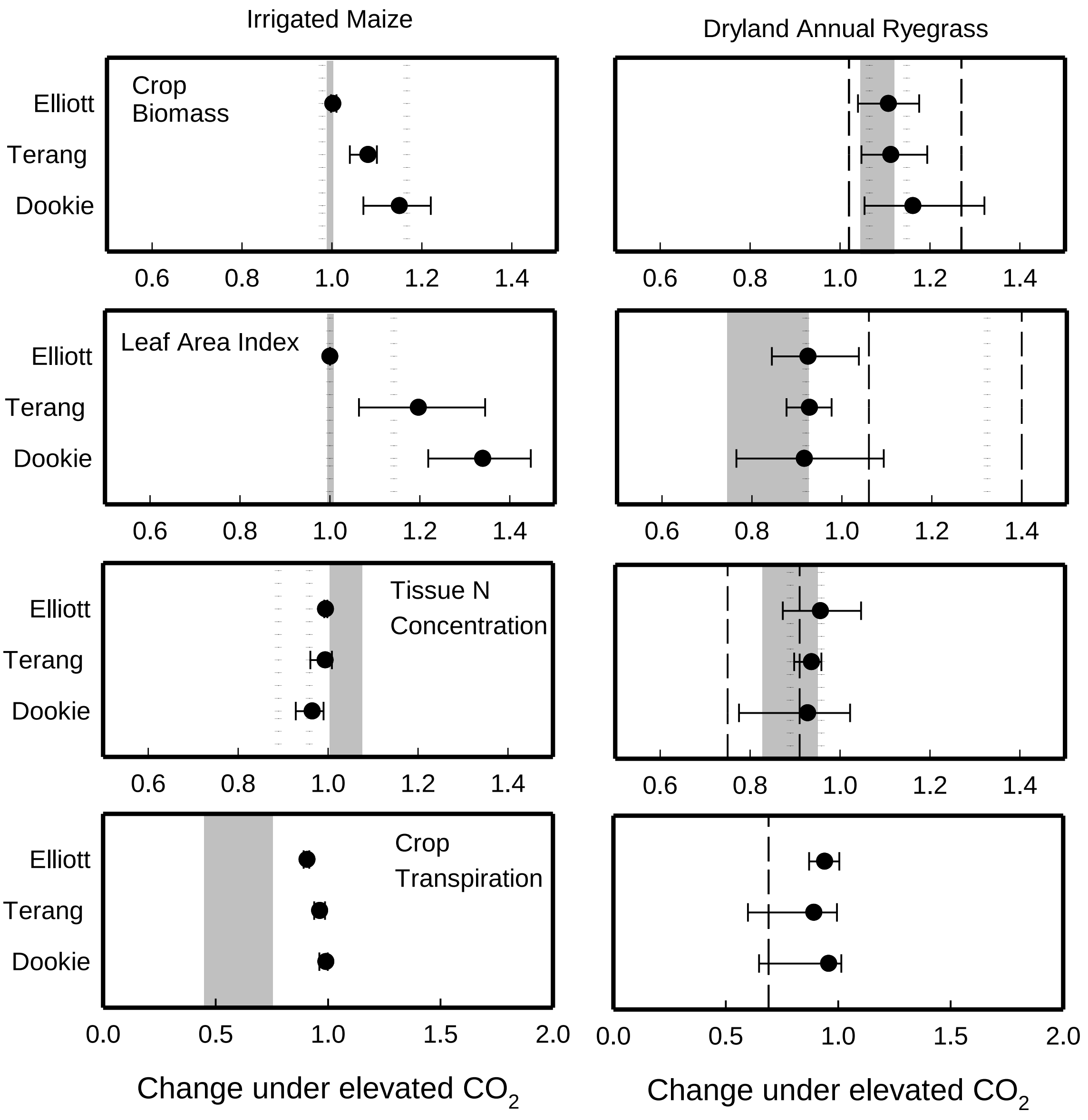

Fig. 2. The mean simulated effect (error bars represent the range in values) of elevated CO_2 (c.a. 600ppm) on crop biomass, leaf area index, tissue nitrogen (N) concentration, and crop transpiration of irrigated maize and dryland annual ryegrass crops compared to previously published effects observed in FACE experiments as outlined in Online supplemental table 3 (represented by the grey areas and closely related species represented by the vertical broken lines) and the effect reported for the most relevant function plant group reported in the meta analysis and literature review undertaken by Ainsworth and Long (2005) (represented by the vertical dotted lines) where that data was available. An effect less than 1 indicates a decrease while an effect greater than 1 indicates an increase.

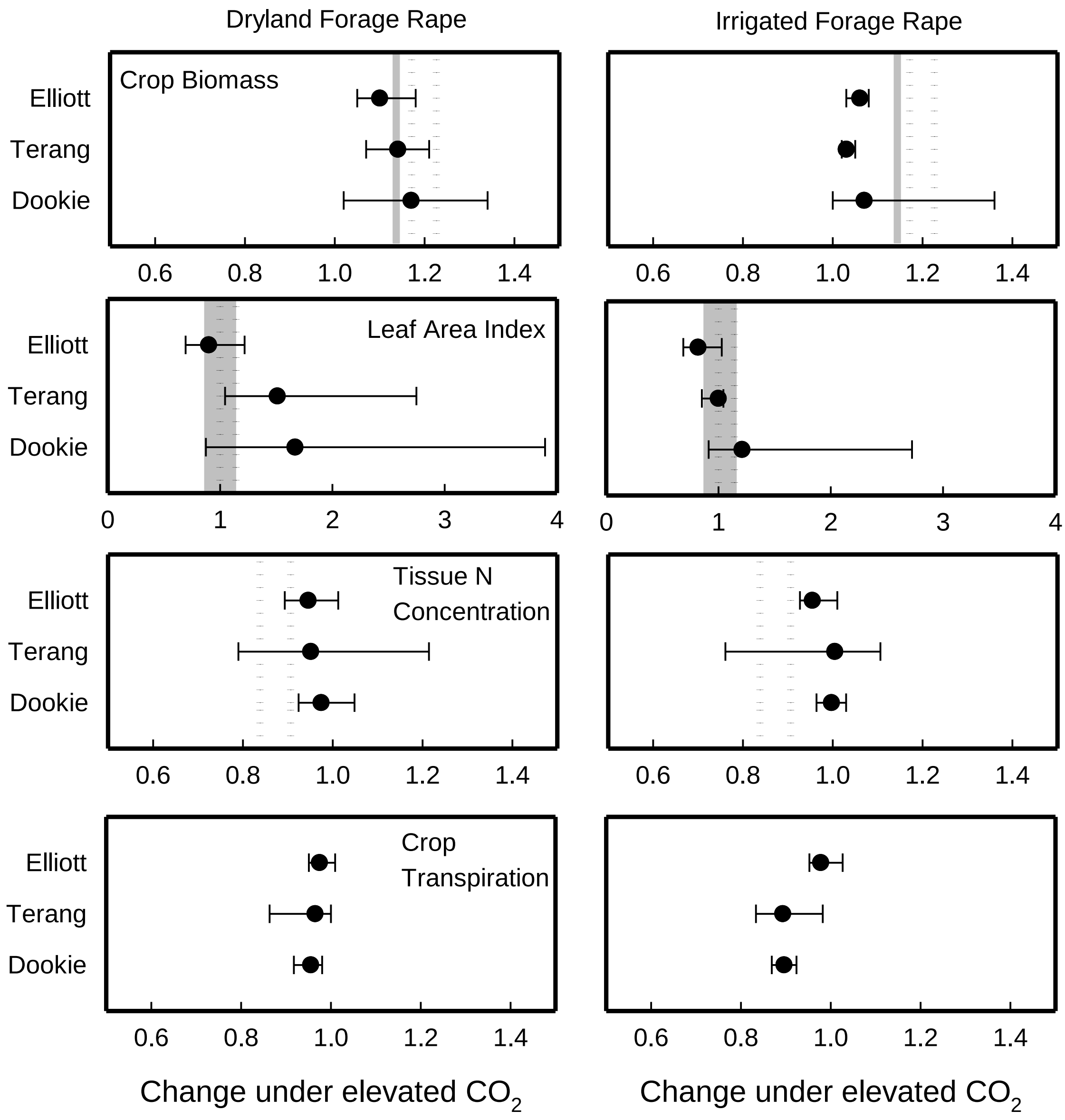

Fig. 3. The mean simulated effect (error bars represent the range in values) of elevated CO_2 (c.a. 600ppm) on crop biomass, leaf area index, tissue nitrogen (N) concentration, and crop transpiration of irrigated and dryland forage rape crops compared to previously published effects observed in FACE experiments as outlined in online supplemental table 3 (represented by the grey areas) and the effect reported for the most relevant function plant group reported in the meta analysis and literature review undertaken by Ainsworth and Long (2005) (represented by the vertical dotted lines) where that data was available. An effect less than 1 indicates a decrease while an effect greater than 1 indicates an increase.

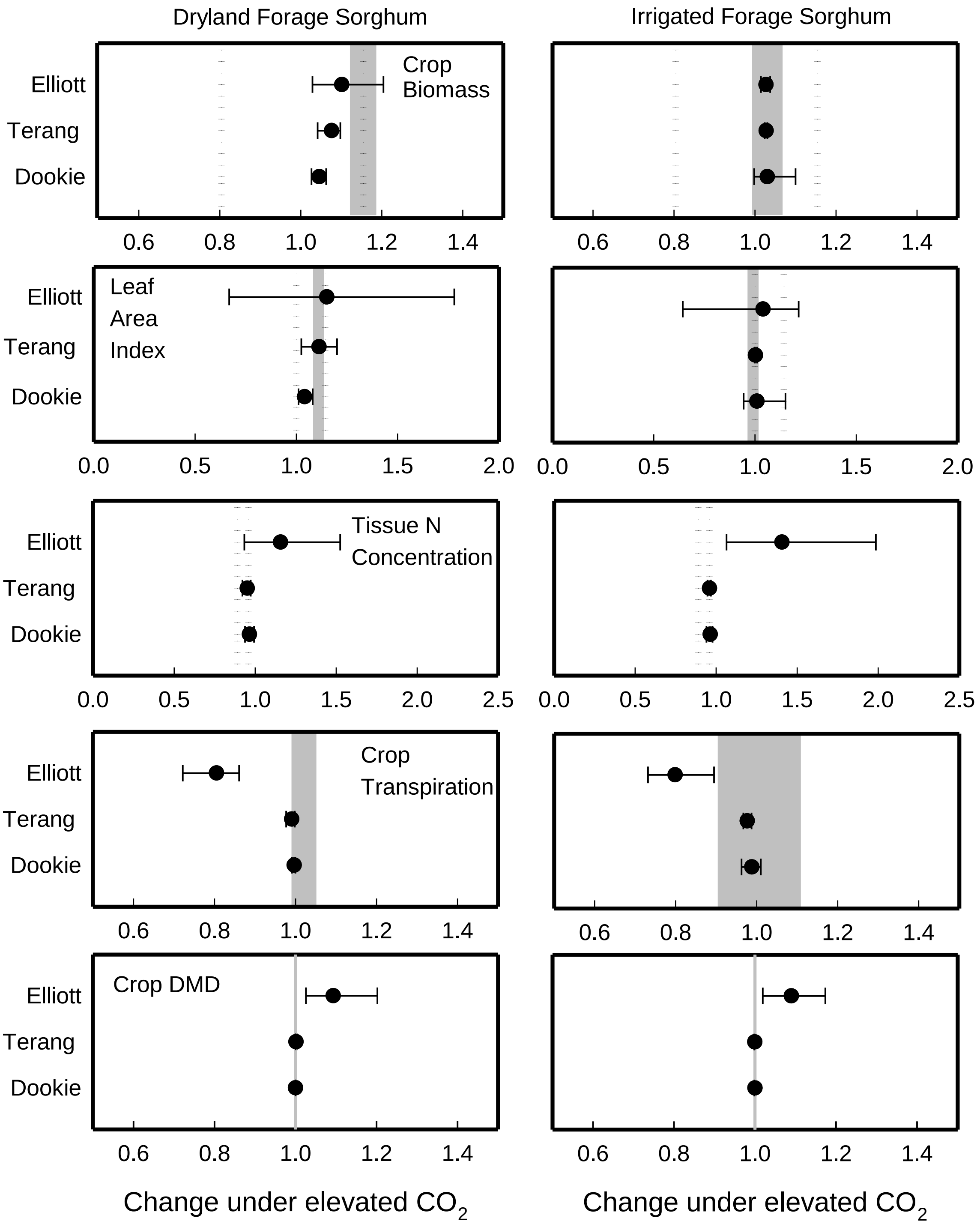

Fig. 4. The mean simulated effect (error bars represent the range in values) of elevated CO_2 (c.a. 600ppm) on crop biomass, leaf area index, tissue nitrogen (N) concentration, crop transpiration and crop dry matter digestibility (DMD) of irrigated and dryland forage sorghum crops compared to previously published effects observed in FACE experiments as outlined in online supplemental table 3 (represented by the grey areas and closely related species represented by the vertical broken lines) and the effect reported for the most relevant function plant group reported in the meta analysis and literature review undertaken by Ainsworth and Long (2005) (represented by the vertical dotted lines) where that data was available. An effect less than 1 indicates a decrease while an effect greater than 1 indicates an increase.

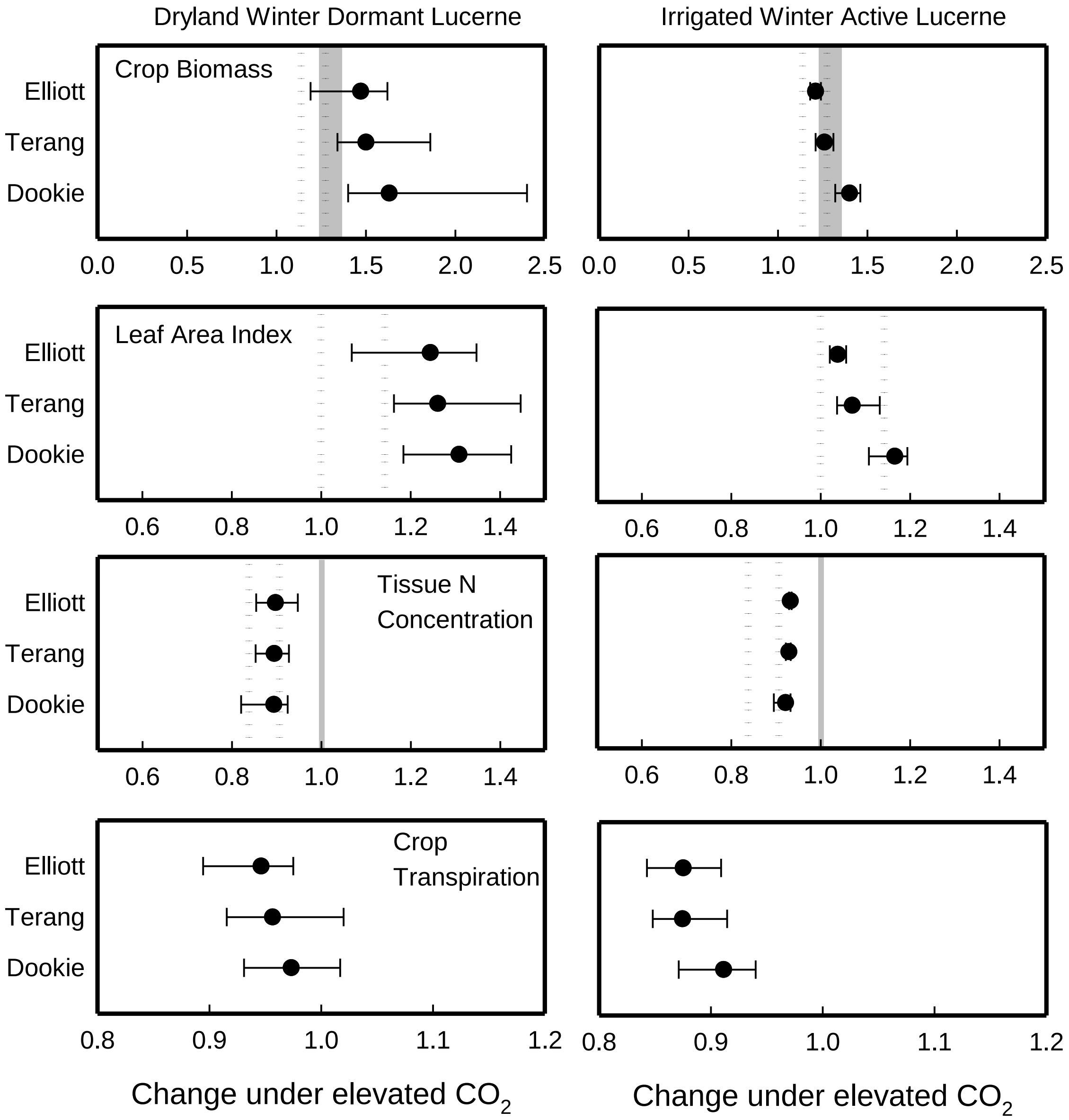

Fig. 5. The mean simulated effect (error bars represent the range in values) of elevated CO_2 (c.a. 600ppm) on crop biomass, leaf area index, tissue nitrogen (N) concentration, and crop transpiration of irrigated winter active and dryland winter dormant lucerne crops compared to previously published effects observed in FACE experiments as outlined in online supplemental table 3 (represented by the grey areas) and the effect reported for the most relevant function plant group reported in the meta analysis and literature review undertaken by Ainsworth and Long (2005) (represented by the vertical dotted lines) where that data was available. An effect less than 1 indicates a decrease while an effect greater than 1 indicates an increase.

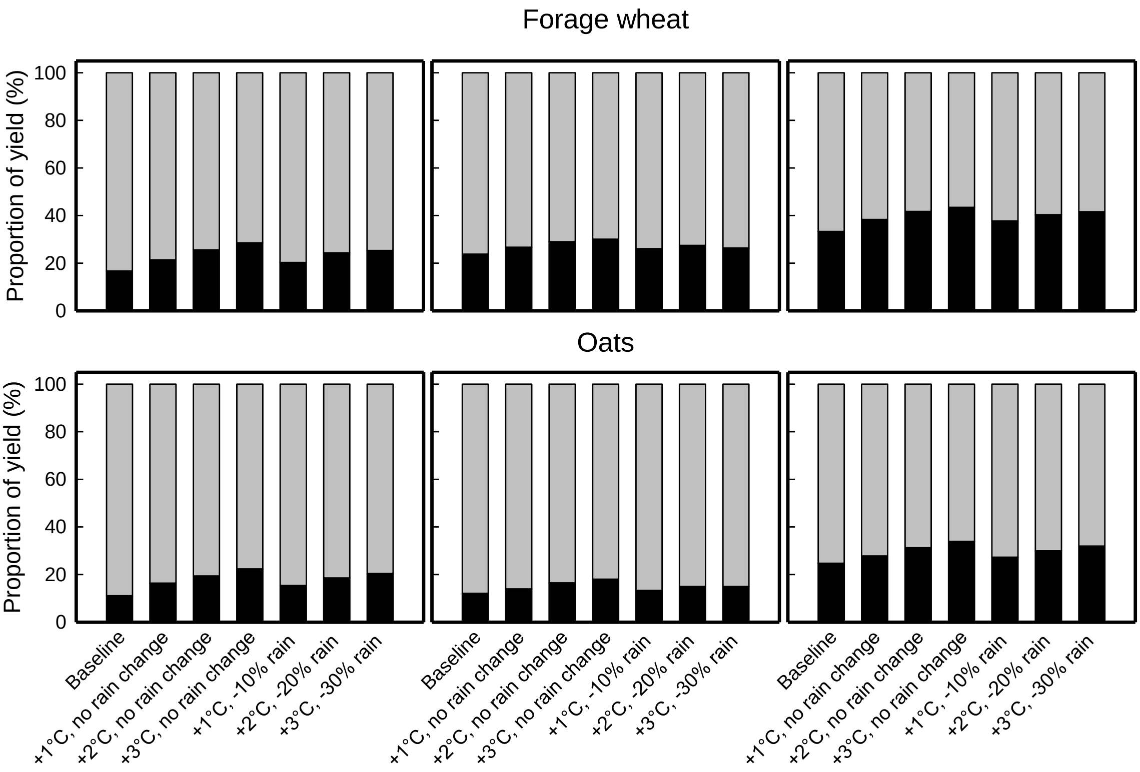

Fig 6 The proportion of total annual production that is grazed (black) or ensiled (grey) of forage wheat and oats for the baseline climate and scenarios with +1, +2, +3°C, +1°C with -10% rain, +2°C with -20% rain and +3°C with -30% rain at Dookie, Victoria (left panels), Terang, Victoria (middle panels) and Elliott, Tasmania (right panels). Increases in air temperatures of 1, 2 and 3^{o}C were associated with atmospheric CO_2 concentrations of 435, 535 and 640 ppm respectively while the baseline scenario had an atmospheric CO_2 concentration of 380 ppm.

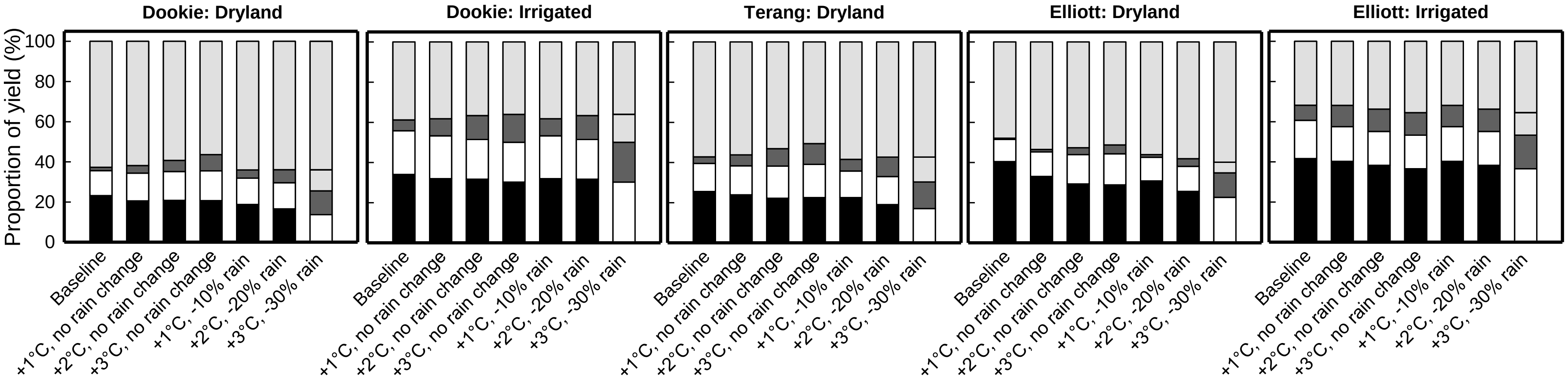

Fig 7 The proportion of DM yield that is available in summer (black), autumn (white), winter (dark grey) and spring (light grey) of lucerne crops grown at Dookie under dryland conditions (far left panel), Dookie under irrigated conditions (inner left panel), Terang under dryland conditions (middle panel), Elliott under dryland conditions (inner right panel) and Elliott under irrigated conditions (far right panel). When alfalfa growth was simulated under dryland conditions the winter dormant genotype was used while under irrigated conditions a winter active genotype was used. Increases in air temperatures of 1, 2 and 3^{o}C were associated with atmospheric CO_2 concentrations of 435, 535 and 640 ppm respectively while the baseline had an atmospheric CO_2 concentration of 380 ppm.

Supplemental online table to:

Modelling the resilience of forage crop production to future climate change in the dairy regions of south eastern Australia using APSIM.

Journal title: Journal of Agricultural Science

Supplementary table 1. The range in published responses of crop biomass, tissue N concentration, transpiration, leaf area index (LAI) and forage dry matter digestibility (DMD) to elevated CO_2 under free air CO_2 enrichment (FACE; ca 500 to 600 ppm of CO_2) of each crop species or related species used to assess the appropriateness of the modifier functions developed reflect the effect of elevated CO_2 on forage crops grown in the south east dairy regions of Australia.

Response	Range in published response	Source
Lucerne		
Crop biomass	24 to 35%	Luscher *et al.* (2000)
Tissue N conc.	-0.1 to -0.2%	Luscher *et al.* (2000)
Maize		
Crop biomass	-0.3%	Leakey *et al.* (2006)
Tissue N conc.	0 to 8%	Leakey *et al.* (2006)
Transpiration	-25 to -56%	Leakey *et al.* (2006)
LAI	0.4%	Leakey *et al.* (2006)
Forage rape		
Crop biomass (oil seed rape)	14%	Franzaring *et al.* (2008)
LAI (oil seed rape)	-14 to 15%	Franzaring *et al.* (2008)
Forage sorghum		
Crop biomass (grain sorghum)	13 to 18% (dryland) -1 to 7% (irrigated)	Ottman *et al.* (2001)
Transpiration (grain sorghum)	-0.3 to 5% (dryland) -9 to 11% (irrigated)	Conley *et al.* (2001)
LAI (grain sorghum)	10 to 14% (dryland) -4 to -0.5% (irrigated)	Ottman *et al.* (2001)
DMD (*Sorghum* × *drummondii*)	-0.0% (dryland) 0.0% (irrigated)	Akin *et al.* (1994)
Annual Ryegrass		
Crop biomass	5 to 12%	Weigel *et al.* (2012)
Crop biomass (perennial ryegrass)	2 to 27%	16.6 to 20.2% (Daepp *et al.* 2001); 5.8 to 20.1% (Daepp *et al.* 2000); 17 to 23% (Suter *et al.* 2001); 2 to 27% (Hebeisen *et al.* 1997);
Tissue N conc.	-5 to -17%	Weigel *et al.* (2012)
Tissue N conc. (perennial ryegrass)	-9 to -25%	-9 to -25% (Daepp *et al.* 2000); -12 to -25% (Zanetti *et al.* 1997)
Transpiration (perennial ryegrass)	-31%	Nijs *et al.* (1997)
LAI	-8 to -26%	Weigel *et al.* (2012)
LAI (perennial ryegrass)	6 to 40%	22 to 40% (Daepp *et al.* 2001); 6 to 23% (Suter *et al.* 2001)
Wheat		
Crop biomass	8 to 27%	17-21% (Kimball *et al.* 1995); 20% (Pinter *et al.* 1996); 27% (Ma *et al.* 2007); 12% (Hogy *et al.* 2009); 10% (Hogy *et al.* 2010) 13 to 26% (Lam *et al.* 2012a); 8 to 12% (Weigel *et al.* 2012)
Tissue N conc.	-3 to -29%	-12 to -29% (Porteaus *et al.* 2009); -3 to -16% (Weigel *et al.* 2012); -4 to -9% (Lam *et al.* 2012b)
Transpiration	-1 to -20%	-7 to -20% (Kimball *et al.* 1999); -1 to -4% (Hunsaker *et al.* 2000)
LAI	2 to 27%	2 to 8% (Kimball *et al.* 1995); 9 to 27% (Tausz-Posch *et al.* 2012); 10 to 20% (Pinter *et al.* 1996)
DMD	-18% to 2%	Akin *et al.* (1995)

References cited

AKIN D. E. , KIMBALL B. A., MAUNEY J. R., LAMORTE R. L., HENDREY G. R., LEWIN K., NAGY J., GATES R. N. (1994) Influence of enhanced CO2 concentration and irrigation on sudangrass digestibility. *Agricultural and Forest Meteorology* **70**, 279-287.

AKIN D. E., KIMBALL B. A., WINDHAM W. R., PINTER P. J., WALL G. W., GARCIA R. L., LAMORTE R. L., MORRISON W. H. (1995) Effect of free-air CO2 enrichment (FACE) on forage quality of wheat. *Animal Feed Science and Technology* **53**, 29-43.

CONLEY M. M., KIMBALL B. A., BROOKS T. J., PINTER P. J. JR., HUNSAKER D. J., WALL G. W., ADAM N. R., LAMORTE R. L., MATTHIAS A. D., THOMPSON T. L., LEAVITT S. W., OTTMAN M. J., COUSINS A. B., TRIGGS J. M. (2001) CO2 enrichment increases water-use efficiency in sorghum. *New Phytologist* **151**, 407-412.

DAEPP M., SUTER D., ALMEIDA J. P. F., ISOPP H., HARTWIG U. A., FREHNER M., BLUM H., NOSBERGER J., LUSCHER A. (2000) Yield response of *Lolium perenne* swards to free air CO2 enrichment increased over six years in a high N input system on fertile soil. *Global Change Biology* **6**, 805-816.

DAEPP M., NOSBERGER J., LUSCHER A. (2001) Nitrogen fertilization and developmental stage alter the response of *Lolium perenne* to elevated CO2. *New Phytologist* **150**, 347-358.

FRANZARING J., HOGY P., FANGMEIER A. (2008) Effects of free-air CO2 enrichment on the growth of summer oilseed rape (*Brassica napus* cv. Campino). *Agricultural Ecosystems and Environment* **128**, 127-134.

HEBEISEN T., LUSCHER A., ZANETTI S., FISCHER B. U., HARTWIG U. A., FREHNER M., HENDREY G. R., BLUM H., NOSBERGER J. (1997) Growth response of *Trifolium repens* L and *Lolium perenne* L as monocultures and bi-species mixture to free air CO2 enrichment and management. *Global Change Biology* **3**, 149-160.

HOGY P., KECK M., NIEHAUS K., FRANZARING J., FANGMEIER A. (2010) Effects of atmospheric CO(2) enrichment on biomass, yield and low molecular weight metabolites in wheat grain. *Journal of Cereal Science* **52**, 215-220.

HOGY P., WIESER H., KOHLER P., SCHWADORF K., BREUER J., FRANZARING J., MUNTIFERING R., FANGMEIER A. (2009) Effects of elevated CO(2) on grain yield and quality of wheat: results from a 3-year free-air CO(2) enrichment experiment. *Plant Biology* **11**, 60-69.

HUNSAKER D. J., KIMBALL B. A., PINTER P. J., WALL G. W., LAMORTE R. L., ADAMSEN F. J., LEAVITT S. W., THOMPSON T. L., MATTHIAS A. D., BROOKS T. J. (2000) CO2 enrichment and soil nitrogen effects on wheat evapotranspiration and water use efficiency. *Agricultural Forest Meteorology* **104**, 85-105.

KIMBALL B. A., PINTER P. J., GARCIA R. L., LAMORTE R. L., WALL G. W., HUNSAKER D. J., WECHSUNG G., WECHSUNG F., KARTSCHALL T. (1995) Productivity and water use of wheat under free-air CO2 enrichment. *Global Change Biology* **1**, 429-442.

KIMBALL B. A., LAMORTE R. L., PINTER P. J., WALL G. W., HUNSAKER D. J., ADAMSEN F. J., LEAVITT S. W., THOMPSON T. L., MATTHIAS A. D., BROOKS T. J. (1999) Free-air CO2 enrichment and soil nitrogen effects on energy balance and evapotranspiration of wheat. *Water Resource Research* **35**, 1179-1190.

LAM S. K., HAN X., LIN E. D., NORTON R., CHEN D. L. (2012a) Does elevated atmospheric carbon dioxide concentration increase wheat nitrogen demand and recovery of nitrogen applied at stem elongation? *Agriculture Ecosystems and Environment* **155**, 142-146.

LAM S. K., CHEN D. L., NORTON R., ARMSTRONG R. (2012b) Nitrogen demand and the recovery of N-15-labelled fertilizer in wheat grown under elevated carbon dioxide in southern Australia. *Nutrient Cycling and Agroecosystems* **92**, 133-144.

LEAKEY A. D., URIBELARREA M., AINSWORTH E. A., NAIDU S. L., ROGERS A., ORT D. R., LONG S. P. (2006) Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO2 concentration in the absence of drought. *Plant Physiology* **140**, 779-790.

LUSCHER A., HARTWIG U. A., SUTER D., NOSBERGER J. (2000) Direct evidence that symbiotic N2 fixation in fertile grassland is an important trait for a strong response of plants to elevated atmospheric CO2. *Global Change Biology* **6**, 655-662.

MA H. L., ZHU J. G., XIE Z. B., LIU G., ZENG Q., HAN Y. (2007) Responses of rice and winter wheat to free-air CO2 enrichment (China FACE) at rice/wheat rotation system. *Plant and Soil* **294**, 137-146.

NIJS I., FERRIS R., BLUM H., HENDREY G., IMPENS I. (1997) Stomatal regulation in a changing climate: a field study using Free Air Temperature Increase (FATI) and Free Air CO2 enrichment (FACE). *Plant Cell Environment* **20**, 1041-1050

OTTMAN M. J., KIMBALL B. A., PINTER P. J., WALL G. W., VANDERLIP R. L., LEAVITT S. W., LAMORTE R. L., MATTHIAS A. D., BROOKS T. J. (2001) Elevated CO2 increases sorghum biomass under drought conditions. *New Phytologist* **150**, 261-273.

PINTER P. J., KIMBALL B. A., WALL G. W., LAMORTE R. L., ADAMSEN F. J., HUNSAKER D. H. (1996) FACE 1995-96: Effects of Elevated CO, and Soil Nitrogen on Growth Parameters and Yield of Spring Wheat. In *Annual Research. U.S. Water Conservation Laboratory*, (Ed. Dedrick), pp. 75-78, Phoenix: U.S. Water Conservation Laboratory.

PORTEAUS F., HILL J., BALL A. S., PINTER P. J., KIMBALL B. A., WALL G. W., ADAMSEN F. J., HUNSAKER D. J., LAMORTE R. L., LEAVITT S. W., THOMPSON T. L., MATTHIAS A. D., BROOKS T. J., MORRIS C. F. (2009) Effect of Free Air Carbon dioxide Enrichment (FACE) on the chemical composition and nutritive value of wheat grain and straw. *Animal Feed Science and Technology* **149**, 322-332.

SUTER D., NOSBERGER J., LUSCHER A. (2001) Response of perennial ryegrass to free-air CO(2) enrichment (FACE) is related to the dynamics of sward structure during regrowth. *Crop Science* **41**, 810-817.

TAUSZ-POSCH S., SENEWEERA S., NORTON R. M., FITZGERALD G. J., TAUSZ M. (2012) Can a wheat cultivar with high transpiration efficiency maintain its yield advantage over a near-isogenic cultivar under elevated CO2? *Field Crops Research* **133**, 160-166.

WEIGEL H. J., MANDERSCHEID R. (2012) Crop growth responses to free air CO2 enrichment and nitrogen fertilization: Rotating barley, ryegrass, sugar beet and wheat. *European Journal of Agronomy* **43**, 97-107.

ZANETTI S., HARTWIG U. A., VANKESSEL C., LUSCHER A., HEBEISEN T., FREHNER M., FISCHER B. U., HENDREY G. R., BLUM H., NOSBERGER J. (1997) Does nitrogen nutrition restrict the CO2 response of fertile grassland lacking legumes? *Oecologia* **112**, 17-25.