Climate change effects on pasture based dairy systems in south-eastern Australia

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Running title: Dairy forage systems under future climate change

Abstract

Increases in temperature, along with possible decreases in rainfall will influence the production of forage on Australian dairy farms. A biophysical simulation study was undertaken to compare the performance of perennial pastures and annual forage cropping systems under historical and two possible future climate scenarios for three key dairy locations of south-eastern Australia. Pastures and forage cropping systems were simulated with the biophysical models DairyMod and APSIM, respectively for a location with a heavy reliance on irrigation (Dookie, Victoria), a location with a partial reliance on irrigation (Elliott, Tasmania) and a dryland location (Terang, Victoria). The historical climate scenario (baseline scenario) had no augmentation to climate data and an atmospheric CO_2 concentration of 380 ppm, while the two future climate scenarios had either a 1^{o}C increase in temperatures (with an atmospheric CO_2 concentration of 435 ppm) and a concurrent 10% decrease in rainfall (+1/-10 scenario) or a 2^{o}C increase in temperatures (with an atmospheric CO_2 concentration of 535 ppm) and a concurrent 20% decrease in rainfall and (+2/-20 scenario). Mean annual dry matter (DM) yields (t DM/ha) at Dookie of the forage cropping options and the pasture systems increased under both the future climate scenarios but more irrigation was required. At Terang, the forage cropping systems increased yield while the yield of the pasture systems decreased under the future climate senarious. At Elliott, irrigated pastures and cropping systems increase yield while there was minimal or a negative impact on dryland pastures and cropping systems yields under the futre climate senarious. At all three locations forage production in the colder months of the year increased with a decrease in production during the warmer months. This study indicates that double cropping and irrigated pasture systems at all three locations appear resilient to projected changes in climate, however, for irrigated systems this assumes a reliable supply of irrigation water. The systems implications of how a shift in the seasonality of forage supply within these options impacts on the farm system as a whole warrants further investigation.

Introduction

Dairy farms in the southeast dairy regions of Australia are typified by a high proportion of homegrown forage in the cow's diet (Fulkerson and Doyle 2001). Although the dominant forage type is perennial pastures, a decade ago up to 19% was supplied by annual crops (Barlow 2008) with this proportion increasing with a continued focus on increasing homegrown forage consumption (Wales and Kolver 2017). Farming systems combining perennial pastures with annual forage crops have been shown to lead to between 11 and 33% higher forage consumption per ha compared to farming systems based on perennial pastures alone (Tharmaraj et al. 2014). Forage production is driven by the prevailing climatic and edaphic conditions and the linkage between inter-seasonal climatic variability and pasture production in southern Australia and New Zealand has been highlighted (Chapman *et al.* 2009; Roche *et al.* 2009). To minimise variability in forage supply, annual forage crops are often grown in rotation with pastures or form part of double or triple cropping forage systems (Chapman *et al.* 2014). These forage systems aim to maximise the efficient use of land, water and nutrients while complementing the supply of forage from perennial pastures (Garcia and Fulkerson 2005; Chapman *et al.* 2014).

For the dairy regions of south-eastern Australia, future climatic projections indicate a general increase in temperature with a concurrent decrease in rainfall (CSIRO and BOM 2015) due to anthropogenic climate change. These changes in climatic conditions will influence forage crop and pasture productivity. However, the overall effect is difficult to directly determine due to the interactions between temperature, water availability and atmospheric CO_2 concentration (Harle *et al.* 2007; Howden *et al.* 2008; McKeon *et al.* 2009). Furthermore, for annual crops, there are likely changes in maturity time, phenological development and residual soil moisture at the conclusion of the crop. These are all critical factors to the success of double and triple cropping systems (Garcia and Fulkerson 2005, Chapman *et al.* 2014). While it is possible to explore the effect of future climate scenarios in the field using free-air CO_2 enrichment (FACE) studies (Kimball *et al.* 2002; McLeod and Long 1999), these studies are expensive to undertake and are limited in scale which limits their use when making regional assessments of a broad range of pasture species and cropping systems.

An alternative is to use biophysical simulation models (e.g. DairyMod; Johnson *et al.* (2008), Agricultural Production Systems sIMulator (APSIM); Holzworth *et al.* (2014);

Keating *et al.* (2003)) that mechanistically integrate various environmental parameters (e.g. temperature, rainfall, atmospheric CO_2 concentration, soil conditions) with crop and pasture management to simulate crop/pasture and soil processes. This approach has been used to explore the impact of anthropogenic driven climate change on grain cropping systems across a range of regions globally (e.g. Reyenga *et al.*(1999), Reyenga *et al.* (2001), Reilly *et al.* (2003), Thomson *et al.* (2006)). For the pastoral regions of south-eastern Australia, Cullen *et al.* (2009) used the biophysical model DairyMod to explore the impact of a warmer and drier climate on the pre-existing pasture base. While the assessments by Cullen *et al.* (2009) are of value and highlight the resilience and vulnerabilities of pasture species, these are only one component of the forage base. To date, there has been no comparative assessment across the entire forage base (both pastures and forage cropping systems). Such an evaluation is required to guide the adaptation of the feedbase and dairy farming systems into the future. The aim of this study was to use the biophysical models APSIM and DairyMod to explore the impact of predicted changes in climate across the “home grown” feedbase of the dairy industry in south-eastern Australia.

Materials and methods

Sites and pasture and crop system simulations

Three sites, Dookie and Terang in Victoria, and Elliott in Tasmania were chosen for this study as they represent a range of climate and management conditions ranging from a dryland system (Terang), a partial reliance on irrigation (Elliott), to a heavy reliance on irrigation (Dookie). Climatic and edaphic conditions at each location are provided in Table 1.

Table 1. Climatic and edaphic (over 1000 mm profile depth) conditions at the three sites used in the current study. Climatic variables were calculated for the period of the simulations (1971 to 2010).

Parameter	Dookie, Victoria	Terang, Victoria	Elliott, Tasmania
Latitude/Longitude	36.4°S/145.7°E	38.15°S/142.6°E	41.1°S/145.8°E,
Soil type^{A}	Vertic calic red chromosol	Brown chromosol	Red mesotrophic haplic ferrosol
Drained upper limit (mm)^{B}	281.0	388.0	406.8
Lower limit (-1500 kpa)^{B}	121.6	276.0	282.8
Total annual rainfall (mm)^{C}	567	733	1196

Total annual evaporation (mm)[C]	1387	1294	1063
Average max temperature in January (°C)[C]	29.3	24.3	20.4
Average min temperature in January (°C)[C]	13.9	11.8	10.9
Average max temperature in July (°C)[C]	11.5	12.9	11.2
Average min temperature in July (°C)[C]	2.5	5.1	4.2
Average vapour pressure (October – March) [C]	12.9	13.0	11.9
Average vapour pressure (April – September) [C]	9.9	10.5	9.9

[A] Isbell (2002)

[B] APsoil (2009)

[C] Calculated from SILO data sets (www.longpaddock.qld.gov.au/silo)

Permanent annual and perennial pastures were simulated with the biophysical pasture model DairyMod (version 4.8.6) using parameters developed and validated in numerous studies (Chapman *et al.* 2008; Cullen *et al.* 2008; Johnson *et al.* 2008; Johnson *et al.* 2003). Pastures simulated were perennial ryegrass (*Lolium perenne* L.) at Elliott, a perennial ryegrass and paspalum (*Paspalum dilatatum* Pior.) pasture mixture and an annual ryegrass (*L. multiflorum* Lam.) pasture at Dookie, and perennial ryegrass and tall fescue (*Festuca arundinacea* Schreb.) pastures at Terang. While DairyMod does not represent cultivars specifically, the pasture growth parameters used are generally representive of the cultivars Impact, Flanker and Fletcha for perennial ryegrass, annual ryegrass and tall fescue respectively. The paspalum parameters represent the naturalised ecotype in Northern Victoria. The model also does not represent endophyte status of plants, however, as it does not represent biotic limitations to plant growth (e.g. damage by pests) it can be assumed that the simulations represented endophyte positive pastures. The perennial ryegrass pasture at Elliott was simulated under both dryland and irrigated conditions. The irrigated pasture was watered to field capacity when a soil water deficit of 15 mm occurred. At Terang, simulations of the perennial ryegrass pasture and tall fescue pasture were simulated under dryland conditions only. At Dookie, the perennial pasture, consisting of a mix of perennial ryegrass and paspalum, was irrigated to field capacity between 15 August and 30 April when a soil water deficit of 22 mm occurred in the upper 500 mm of the soil profile. For the annual ryegrass pasture at Dookie, the same soil water deficit approach to irrigation scheduling was used, but the irrigation season was limited to the period between 15 March to 31 October. At all sites, N fertiliser was applied so that it was not limiting to plant growth. This management within the simulations reflects the current best management practices for pastures at each of the locations. Pasture yields were simulated as a monthly cut trial, with pasture harvested on the last day of each month to a residual of 1.5 t DM/ha.

Lucerne (*Medicago sativa* L.) pastures were simulated using the lucerne module in APSIM (version 7.3) (Robertson *et al.* 2002). This module has previously been evaluated for its ability to accurately simulate the growth and development of lucerne in the southeastern regions of Australia (Dolling *et al.* 2005; Pembleton *et al.* 2011; Zahid *et al.* 2003). Lucerne was simulated under dryland and irrigated conditions at Elliott and irrigated conditions only at Dookie. When lucerne was simulated under dryland conditions a winter dormant genotype was used, while under irrigation a winter active genotype was used (refer to Pembleton *et al.* (2011) for the associated cultivar selection and manager rules to define winter dormant and winter active lucerne genotypes within APSIM). The genotype selection under the different water regimes reflects the recommended use of winter dormant lucerne genotypes under dryland conditions and the recommended use of winter active lucerne genotypes under irrigated conditions in south-eastern Australia (Pembleton *et al.* 2010a; 2010b). Lucerne was defoliated at the early flowering growth stage and irrigation, if applicable, was applied on a soil water deficit of 30 mm.

Annual forage crop systems (including those incorporating annual pastures) were simulated using the relevant crop modules in APSIM (version 7.3). Modification of some crop modules was required (including the addition of forage specific cultivars (via changing genetic coefficients), and addition of parameters to allow the grazing by the livestock module). These modifications and the validation of APSIM for the simulation of forage crops in the south-eastern dairy regions of Australia are described in Pembleton *et al.* (2013). Further modifications to crop modules were made to improve their ability to accurately reflect the influence of changing atmospheric CO_2 concentration on crop production (see Pembleton *et al.* (2016) for details). Forage crop systems were developed in consultation with researchers and crop agronomists working in the southeastern dairy region of Australia and reflected current double-cropping systems employed at each location. Table 2 presents a full description of the management of each of these cropping systems.

To initialise soil carbon, nitrogen and water conditions and surface organic matter pools all simulations had a 10 year initialisation period of dryland pasture (pastures in APSIM were simulated with the AgPasture module; (Li *et al.* 2011)) using baseline climatic data from the period 1961 to 1970 inclusive. Data from this period was not included in any subsequent analysis.

Table 2. Crop agronomic management of the forage cropping systems at Dookie and Terang, Victoria and Elliott, Tasmania simulated with the biophysical crop model APSIM

	Dookie		Terang		Elliott	
Cropping system	Annual ryegrass (AR), Maize for silage (MS) double crop	Annual ryegrass (AR), forage sorghum (FS) double crop	Forage wheat (FW), forage rape (FR) double crop	Annual ryegrass (AR), Forage sorghum (FS) double crop	Oats (O), forage rape (FR) double crop	Annual ryegrass (AR), Maize for silage (MS) double crop
Sowing rules	AR: 15 Mar MS: 10 Nov	AR: 15 Mar FS: 30 Nov	FW: 1 Apr to 15 May after 20 mm of rainfall over 3 days FR: 10 days after the end of FW crop	AR: 1 Apr to 15 May after 20 mm of rainfall over 3 days FS: 10 Nov	O: 20 Apr to 20 May after 20 mm of rainfall over 3 days FR: 6 days after the end of O crop	MS: 10 Nov AR: 6 days after the end of MS crop
Plant/tiller density (plants/m2)	AR: 500 MS: 8.8	AR: 500 FS:40	FW: 200 FR: 75	AR: 500 FS: 40	O: 200 FR: 75	MS: 8.8 AR: 500
Cultivars	AR: late MS: Pioneer3527	AR: late FS: Sugargraze	FW: Wedgetail, FR: Forage	AR: late FS: Sugar graze	O: Taipan FR: Forage	AR: late MS: Pioneer3527
Nitrogen fertiliser (kgN/ha)	AR: 50 at sowing, 50 following grazing, MS: 100 at sowing, 75 at 42 DAS and 75 at 53 DAS	AR: 50 at sowing, 50 following grazing, FS: 30 at sowing, 30 following grazing	FW: 50 at sowing, 50 following grazing FR: 40 at sowing	AR: 50 at sowing, 50 following grazing FS: 50 at sowing	O: 50 at sowing, 75 following grazing FR: 50 at sowing, 25 at 30 DAS	AR: 50 at sowing, 50 following grazing MS: 100 at sowing, 75 at 42 DAS and 75 at 53 DAS
Irrigation management	AR and MS: 100 mm applied at sowing. MS: irrigated on a 100mm SWD	AR and FS: 100 mm applied at sowing.	Dryland	Dryland	Dryland	MS: irrigated on a 40mm SWD
Grazing management	AR: Grazed when biomass > 2800 kgDM/ha to a residual of 1500 kgDM/ha	AR: Grazed when biomass > 2800 kgDM/ha to a residual of 1500 kgDM/ha FS: Grazed when biomass > 3000 kgDM/ha to a residual of 800 kgDM/ha	FW: Grazed 30 days after reaching a Zadok stage of 25 FR: Grazed when biomass > 2800 kgDM/ha to a residual of 800 kgDM/ha	AR: Grazed when biomass > 2800 kgDM/ha to a residual of 1500 kgDM/ha FS: Grazed when biomass > 3000 kgDM/ha to a residual of 800 kgDM/ha	O: grazed 30 days after reaching a Zadok stage of 25 FR: Grazed at 98 DAS	AR: grazed when biomass > 2800 kgDM/ha to a residual of 1500 kgDM/ha
Silage harvest/crop termination rules	AR: Terminated on 31 Oct MS: Harvested for silage at milk line score of 2.5 (APSIM growth stage of 8.5)	AR: Terminated on 31 Oct FS: Terminated on 28 Feb	FW: Crop harvested for silage when reached a Zadok stage of 45 (booting) FR: Terminated after 2nd grazing or on 29 Mar	AR: Terminated on 31 Oct FS: Terminated on 28 Feb	O: Crop harvested for silage when reached a Zadok stage of 45 (booting) FR: Terminated after grazing (98 DAS)	AR: Terminated on 31 Oct MS: Harvested for silage at milk line score of 2.5 (APSIM growth stage of 8.5)

Future climate scenarios

A historical baseline and two future climate scenarios were used to assess the effects of climate change on the simulated forage systems. The historical baseline climate data was sourced as patched point data sets of daily weather data from the silo database (Jeffrey *et al.* 2001; www.longpaddock.qld.gov.au/silo). The future climate scenarios were created by augmenting the historical data with 1°C increase in maximum and minimum temperatures and a 10% decrease in daily rainfall (from here on referred to as the +1/-10 scenario), or a 2°C increase in maximum and minimum temperatures and a 20% decrease in daily rainfall (from here on referred to as the +2/-20 scenario). These scenarios were used to test the sensitivity of the system to the warmer and drier climates projected for southern Australia (CSIRO and Bureau of Meteorology 2015). The associative atmospheric CO_2 concentration was 380, 435 and 535 ppm, for the baseline, +1/-10 and +2/-20 climate scenarios, respectively.

Model output and data analysis

For all forage crop and lucerne pastures the forage avalible for grazeing were calculated as the forage grown over the grazing window plus the crop/pasture yield above the the post grazing residual at the start of this period. For the grass pastures monthly cut yields were summed to give the forage avalible for grazeing. Silage yields (if applicable) in each crop was the crop biomass at harvest above harvest height. Irrigation requirements per crop were calculated as the aggregate amount of irrigation applied from planting to the final grazing or silage harvest. Water use efficiency (WUE) of each irrigated annual pasture and forage crop system was calculated as the quotient of the annual total DM yield and the annual total water used where annual water used was the sum of rainfall plus irrigation plus change in soil water content. The WUE of the perennial pastures and lucerne crops was calculated as the quotient of the annual total DM yield and the annual total water received (rainfall plus irrigation) to that system. Due to inter-correlations between the input climate data and the model output data and the mechanistic, non-stochastic nature of the models no formal statistical analysis was undertaken.

Results

DM yields

In comparison to the baseline scenario, the median annual DM yield of each forage system increased under each of the future climate scenarios with the exception of perennial ryegrass and tall fescue pastures at Terang which decreased under both the +1/-10 and the +2 /-20 scenarios, the dryland perennial ryegrass pasture at Elliott which decreased under the +2/ -20 scenario only and the annual ryegrass/maize double-crop grown at Dookie (Figure 1). The median annual DM yield of the annual ryegrass/maize double-crop grown at Dookie was 31.6 t DM/ha under the baseline scenario with a 3% change under +2/-20 scenarios. At Elliott, the median DM yield of the annual ryegrass/maize double cropping system was 27.7 t DM/ha under the baseline scenario with a 9% and 16% positive change under the +1/-10 and +2/-20 scenarios respectively. Variability (as indicated by the CV) in annual DM production of forage systems grown with irrigation was relatively consistent or decreased slightly under the future climate scenarios relative to the baseline. The variability in the annual yield of the dryland forage systems increased under the future climate scenarios apart from the dryland forage oats/dryland forage rape double-crop grown at Elliott where there was a decrease in the CV in total annual yield under the future climate scenarios compared to the baseline.

Within the double-cropping systems, the winter crop component (annual ryegrass, forage wheat or oats) increased its contribution to the total annual yield of these systems with an associated decrease in the contribution from the summer crop (maize, forage sorghum or forage rape) (Table 3) under both the future climate scenarios. The exception to this was the oats/forage rape double cropping system at Elliott, where the contribution from the forage rape crop to total DM yield increased by 1% in the +1/-10 scenario during this period.

For the dryland forage crop systems at Terang and Elliott, forage availability decreased relative to the baseline in summer (Table 4). In contrast, the increase in forage availability between the baseline and the +1/-10 and +2/-20 climate scenarios was most evident in winter or spring. The irrigated pasture and the irrigated winter active lucerne systems also had an increase in the forage available for grazing during late spring through to autumn under the future climates with the exception of the irrigated perennial ryegrass pasture at Elliott which had a slight decrease in forage available for grazing under the +2/-20 scenario.

The silage yields from the annual ryegrass/maize double cropping system decreased at Dookie under the future climate scenarios compared to the baseline scenario (Table 5). For the dedicated silage harvests within the double-cropping systems at Elliott and Terang, the

DM yield increased under the future climate scenarios compared to the baseline scenario. The median harvest date and the range in harvest dates for all dedicated silage harvests within the double-cropping systems were between 5 and 18 days earlier under the +1/-10 scenario and between 8 and 28 days earlier under the +2/-20 scenario compared to the baseline scenario.

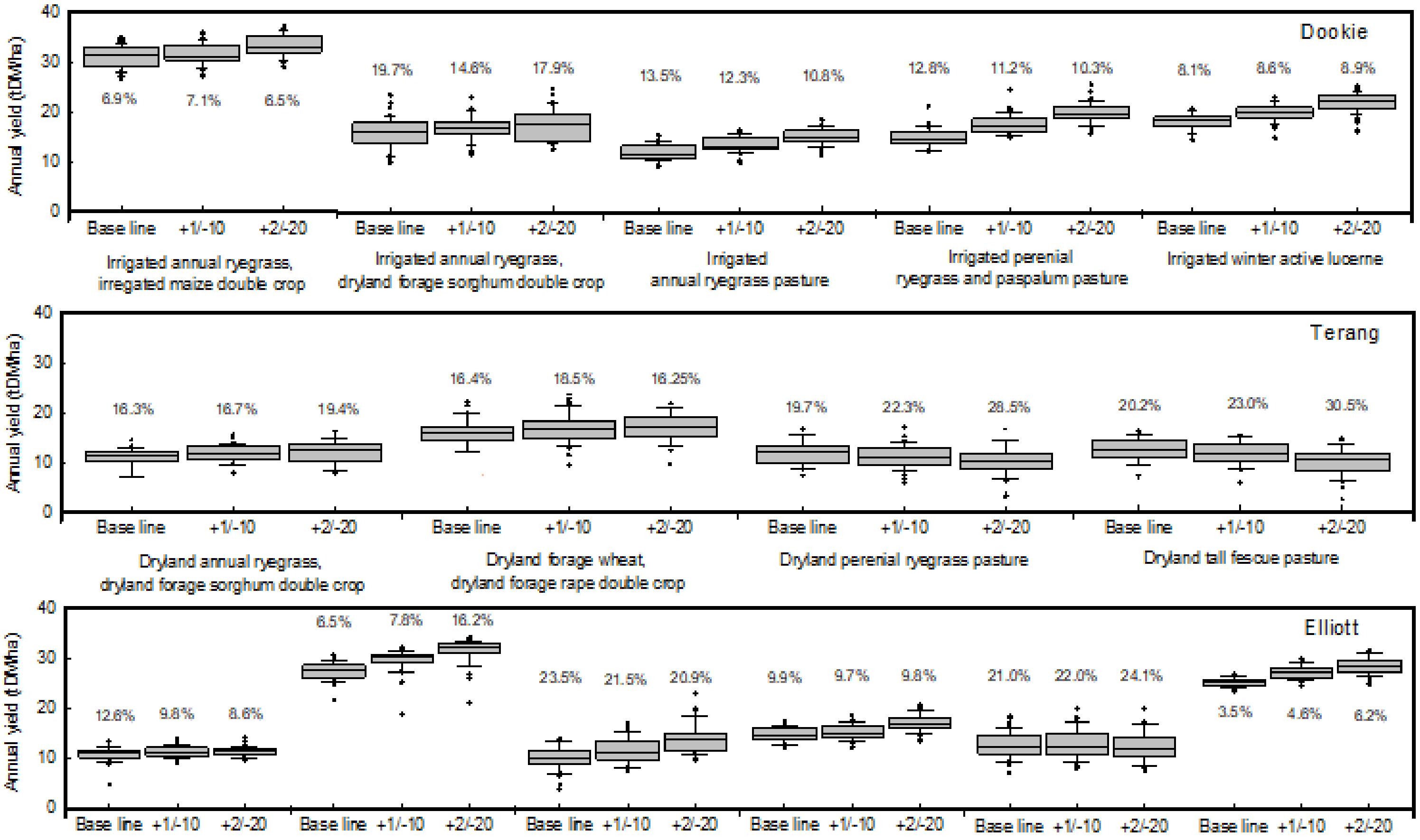

Figure 1. Box and whisker plots (lines represent the median, boxes represent the 25th and 75th percentiles, whiskers represent the 5th and 95th percentiles and dots (•) represent outliers) of the total annual yield of each forage system simulated for Dookie and Terang, Victoria and Elliott, Tasmania over 40 years (1971 to 2010). Coefficients of variation (CV; %) in total annual yield are also presented for each forage system.

Table 3. Average contribution (% of annual DM yield) of the winter crop to the total annual DM yield within of the double-cropping systems simulated over 40 years (1971 to 2010) at Dookie and Terang, Victoria and Elliott, Tasmania. Values in parenthesis are the range in the contribution.

Cropping system	Climate scenario	Contribution of the winter crop to annual DM yield
	Dookie, Victoria	
Annual ryegrass, maize double crop	Baseline	37% (30-43%)
	+1/-10	40% (33-46%)
	+2/-20	43% (33-48%)
Annual ryegrass, forage sorghum double crop	Baseline	75% (50-100%)
	+1/-10	75% (53-100%)
	+2/-20	81% (56-100%)
	Terang, Victoria	
Forage wheat, forage rape double crop	Baseline	62% (50-90%)
	+1/-10	65% (52-100%)
	+2/-20	68% (53-100%)
Annual ryegrass, forage sorghum double crop	Baseline	72% (53-100%)
	+1/-10	76% (56-100%)
	+2/-20	83% (63-100%)
	Elliott, Tasmania	
Oats, forage rape double crop	Baseline	78% (69-13%)
	+1/-10	77% (71-85%)
	+2/-20	81% (74-89%)
Annual ryegrass, maize double crop	Baseline	15% (11-17%)
	+1/-10	19% (15-22%)
	+2/-20	24% (17-28%)

Table 4. Average forage yield (t DM/ha) avalible for grazing by season for each of the forage systems (double cropping and perennial pastures) at Dookie and Terang, Victoria and Elliott, Tasmania. Values are the average of 40-year simulations (1971 to 2010).

System	Scenario	Summer	Autumn	Winter	Spring
	Dookie, Victoria				
Annual ryegrass, forage sorghum double crop	Baseline	4.5	3.8	2.8	4.9
	+1 - 10	4.6	4.0	3.2	5.3
	+2 - 20	3.9	4.2	4.2	5.7
Annual ryegrass, maize double crop	Baseline	0	3.8	2.8	4.9
	+1 - 10	0	4.0	3.2	5.3
	+2 - 20	0	4.2	4.2	5.7
Annual ryegrass pasture	Baseline	0	2.2	3.6	6.0
	+1 - 10	0	2.4	4.4	6.6
	+2 - 20	0	2.7	5.1	7.1
Perennial ryegrass paspalum pasture	Baseline	5.4	2.2	1.2	6.0
	+1 - 10	6.4	2.8	1.6	6.7

	+2 - 20	7.4	3.4	1.8	7.1
Winter active lucerne	Baseline	6.1	4.0	1.0	6.9
	+1 - 10	6.3	4.3	1.7	7.6
	+2 - 20	6.8	4.5	2.7	8.0
Terang, Victoria					
Forage wheat, forage rape double crop	Baseline	5.3	0.9	2.0	0
	+1 - 10	5.3	0.9	2.4	0.0
	+2 - 20	4.9	0.9	2.7	0
Annual ryegrass, forage sorghum double crop	Baseline	3.1	0.2	2.9	4.4
	+1 - 10	2.9	0.3	3.3	4.7
	+2 - 20	2.2	0.3	4.0	5.0
Perennial ryegrass	Baseline	1.3	0.4	2.5	6.9
	+1 - 10	0.9	0.2	2.6	6.8
	+2 - 20	0.5	0.0	2.5	6.4
Tall fescue	Baseline	2.6	0.7	2.1	6.6
	+1 - 10	1.9	0.2	2.1	6.8
	+2 - 20	1.0	0.0	1.7	6.5
Elliott, Tasmania					
Oats, forage rape double crop	Baseline	2.4	0	1.6	0
	+1 - 10	2.6	0	1.8	0
	+2 - 20	2.2	0	2.0	0
Annual ryegrass , maize double crop	Baseline	0	0	0.6	3.4
	+1 - 10	0	0.0	1.9	3.6
	+2 - 20	0	0.3	2.7	4.4
Dryland winter dormant lucerne	Baseline	4.2	1.1	0.0	4.9
	+1 - 10	3.7	1.4	0.2	6.6
	+2 - 20	3.7	1.8	0.5	8.2
Irrigated winter active lucerne	Baseline	5.0	2.9	1.3	5.5
	+1 - 10	5.2	3.0	1.4	5.6
	+2 - 20	5.9	3.5	1.5	6.2
Dryland perennial ryegrass	Baseline	3.2	1.5	2.0	6.0
	+1 - 10	2.8	1.2	2.3	6.5
	+2 - 20	2.5	0.8	1.4	6.4
Irrigated perennial ryegrass	Baseline	10.6	4.5	2.1	8.0
	+1 - 10	10.9	4.7	2.5	9.0
	+2 - 20	9.2	3.4	1.6	8.3

Table 5. Effect of future climate scenarios on silage production, (t DM/ha) and date of harvest, within forage cropping systems at Dookie, Terang, and Elliott. Values in parenthesis are the coefficient of variation (CV; %) in DM yield.

Crop	Cropping system	Climate scenario	Average silage yield (t DM/ha)	Median day of year for silage harvest	Range in harvest dates
			Dookie		
Maize	Annual ryegrass, maize double crop	Baseline	19.6 (11.0%)	5-Mar	20 Feb – 12 Mar
		+1/-10	19.1 (11.7%)	28-Feb	18 Feb – 11 Mar
		+2/-20	19.2 (11.2%)	24-Feb	14 Feb – 6 Mar
			Terang		
Forage wheat	Forage wheat, forage rape double crop	Baseline	7.4 (10.4%)	28-Sep	15 Sep – 12 Oct
		+1/-10	7.7 (9.8%)	23-Sep	10 Sep – 3 Oct
		+2/-20	8.0 (10.2%)	20-Sep	6 Sep – 28 Sep
			Elliott		

Oats	Oats, forage rape double crop	Baseline	6.9 (9.3%)	7-Nov	29 Oct – 20 Nov
		+1/-10	7.0 (11.3%)	1-Nov	21 Oct – 12 Nov
		+2/-20	7.2 (10.6%)	26-Oct	12 Oct – 7 Nov
Maize	Annual ryegrass, maize double crop	Baseline	23.4 (6.5%)	17-May	15 Apr – 30 May
		+1/-10	24.1 (8.2%)	29-Apr	6 Apr – 30 May
		+2/-20	24.0 (8.8%)	19-Apr	27 Mar – 30 May

Irrigation requirements and WUE

Under the +1/-10 scenario, the irrigation requirements increased by 17-18% for both the annual ryegrass grown at Dookie and for the annual ryegrass/irrigated maize double-crop at Elliott. For the winter active lucerne under the +1/-10 scenario, there was a slight increase in irrigation requirement at Dookie and a decrease at Elliott (Table 6). For the +2/-20 scenario, the annual ryegrass pasture at Dookie had an increase in irrigation requirement of 51% while the perennial ryegrass system at Elliott had an increase of 26% compared to the baseline scenario. There was a decrease in the irrigation requirement of winter active lucerne at both Elliott and Dookie for the +2/-20 scenario. For all irrigated cropping systems and pastures at both locations, the WUE (kg DM/mm) increased by between 7.2 and 45.0% under both the future climate scenarios.

Table 6. Average irrigation water required (mm) and water use efficiency (WUE; kg DM/mm) of irrigated forage systems under the baseline scenario and the change (%) from the baseline for the future climate scenarios for irrigated forage systems at Dookie, Victoria and Elliott, Tasmania. Values are the average of 40-year simulations (1971 to 2010). Values in parenthesis are for the WUE.

	Climate scenario					
Forage system	Baseline		+1/-10		+2/-20	
	Irrigation water required (mm)	WUE (kg DM/mm)	Irrigation water required (% change from the baseline)	WUE (% change from the baseline)	Irrigation water required (% change from the baseline)	WUE (% change from the baseline)
		Dookie, Victoria				
Irrigated annual ryegrass, irrigated maize double crop	457	32.0	2.4%	7.2%	13.9%	13.5%
Irrigated annual ryegrass, dryland forage sorghum double crop	200	20.4	10.9%	10.2%	34.0%	16.2%
Irrigated annual ryegrass pasture	232	15.2	16.8%	16.2%	51.1%	27.2%
Irrigated perennial ryegrass paspalum pasture	591	12.8	13.3%	16.6%	26.1%	25.9%
Irrigated winter active lucerne	527	16.5	1.3%	14.6%	-1.3%	31.9%
		Elliott, Tasmania				
Annual ryegrass, irrigated maize double crop	195	20.3	16.6%	16.5%	26.9%	27.9%
Irrigated perennial ryegrass pasture	337	16.4	13.2%	13.1%	25.6%	24.6%
Irrigated winter active lucerne	212	11.9	-10.9%	15.4%	-13.9%	45.0%

Residual soil moisture and crop failure in double cropping systems

For the dryland double-cropping systems, the frequency of crop failures (defined as when a crop failed to reach the predetermined thresholds for grazing or silage harvest) varied between the different climate scenarios (Table 7). At Dookie the frequency of crop failure within the annual ryegrass/forage sorghum double cropping system halved under the +1/-10 scenario but increased under the +2/-20 scenario. Across all the climate scenarios at Elliott there were no crop failures over the 40-year simulation period. In both the double-cropping systems at Terang the frequency of crop failure increased under the future climate scenarios. The greatest increase in the frequency of crop failure at this location was for the annual ryegrass/sorghum double-crop which reached a 43% frequency (17 years out of 40) of crop failure under the +2/-20 scenario, compared to 18% and 23% under the baseline and +1/-20 scenarios, respectively.

For all three climate scenarios, the correlation coefficient between residual plant-available soil water at sowing and final yield of dryland summer crops grown as part of double-cropping systems was highest (R > 0.69) for the forage sorghum sown after annual ryegrass at Dookie (Figure 2). Correlations between plant-available soil water and DM yield were also strong (R > 0.56) for the forage sorghum sown at Terang. Correlations were weak (R < 0.48) for the forage rape sown after forage wheat at Terang or sown after oats at Elliott. The correlations were weaker under both future climate scenarios at Elliott and the +1/-10 scenario at Terang.

Table 7. Frequency (years out of 40) of summer crop failure within the dryland forage cropping systems simulated at Dookie, Terang, and Elliott, under the baseline and the two future climate scenarios.

		Climate scenario		
Location	Cropping system	Baseline	+1/-10	+2/-20
Dookie	Annual ryegrass/forage sorghum double crop	8	4	10
Terang	Forage wheat/forage rape double crop	0	1	1
	Annual ryegrass/forage sorghum double crop	7	9	17
Elliott	Oats/forage rape double crop	0	0	0

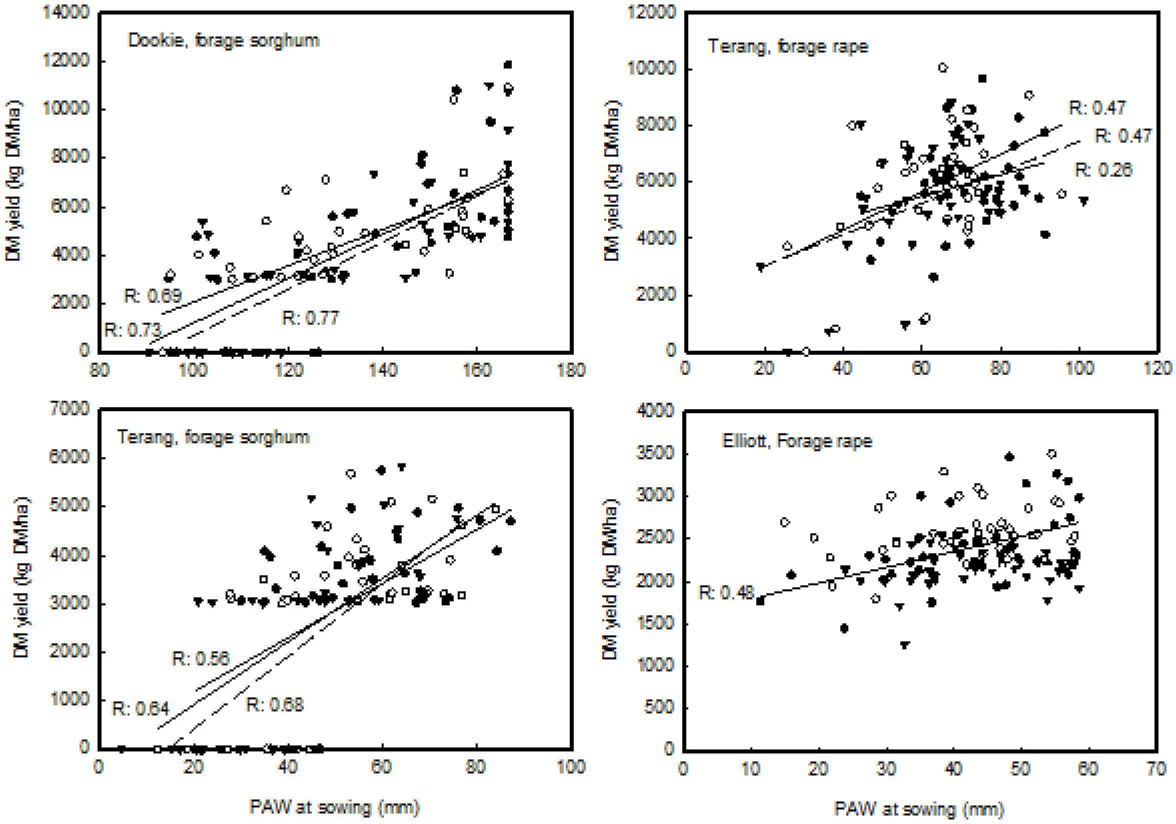

Figure 2. The correlation between the root zone plant available water at sowing and the DM yield of forage crops grown under dryland conditions as part of 40 year simulations (1971 to 2010) of double cropping forage systems at Dookie and Terang, Victoria and Elliott, Tasmania under the baseline (●, thin solid line), the +1/-10 (○, thick solid line) and the +2/-20 (▼, broken line) climate scenarios. Correlations are not shown where R was less than 0.20.

Discussion

This simulation study suggests that the effects of a warmer and drier climate with associated increases in atmospheric CO_2 on the total annual DM yield are minimal for the forage systems examined. Only the dryland perennial pastures at Terang had a decrease in total DM yield under both the +1/-10 and +2/-20 climate scenarios, while dryland perennial ryegrass at Elliott had a slight reduction in total DM yield under the +2/-20 scenario. Simulations undertaken by Cullen *et al.* (2012) for a range of perennial pastures species across a range of temperate and Mediterranean environments identified that perennial pasture species were relatively robust in terms of total annual yield to moderate changes (up to an increase in air temperature of +2^{o}C) in climate.

Despite the robustness in DM yield of each of the forage systems there were changes to the seasonal pattern of production that will influence the farming system. Within the double cropping systems, the winter crops all increased their contribution to the total DM yield, with a subsequent decrease in the contribution to total DM yield from the summer crops. Several of the summer crops investigated were C4 species (i.e. maize and forage sorghum). While perennial C4 pasture species are expected to increase in production in the dairy regions of south-eastern Australia under future climate scenarios (Cullen *et al.* 2012), this study highlights different responses for annual C4 crops in warmer and drier climates. The reason for this apparent contradiction is that the annual C4 forage crops reached harvest maturity earlier under the future climate scenarios relative to the baseline, a factor that has minimal impact on perennial C4 pastures. For dryland C4 crops, such as forage sorghum grown at Terang, there is also an increased chance of crop failure (Table 7). This will change the pattern of forage supply on farms utilising these systems which will have implications for the herds calving pattern and the proportion of the farm area planted to these forage systems.

The increase in the amount of forage available for grazing during winter under the future climates should help fill the winter feed gap present within the current feedbase (Chapman *et al.* 2006; Rawnsley *et al.* 2007; Chapman *et al.* 2014). However, this is countered by a decrease in the availability of forage during the summer months, particularly for the dryland forage systems. Furthermore, the dryland double-cropping systems at Terang and Dookie had a higher chance of crop failure during the summer crop phase under the +2/-20 climate scenario. The comparison of forage rape and sorghum yields at Terang highlights the importance of sowing date and stored soil moisture on summer crop performance. The earlier sown forage rape had higher levels of stored moisture at sowing compared to the later sown forage sorghum, resulting in higher and more reliable yields (Figure 2). This effect is likely to be exacerbated in warmer and drier future climates.

Another aspect of the change in the seasonal pattern of production was the considerable increase in the production of forage for grazing during spring. Spring is a time of oversupply of forage on dairy farms in south-eastern Australia (Chapman *et al.* 2006;

Jacobs *et al.* 1998). To maintain a more constant supply of forage on-farm, surplus forage in spring is conserved as either silage or hay and then fed back to the herd during times of low forage supply (Chapman *et al.* 2014). This prevents an accumulation of relatively high fibrous, low nutritive value forage during the periods of high growth rates in spring. However, conservation imposes additional costs on the production, conservation and handling of forage, along with wastage during the feeding of the conserved forage (Stockdale 2010). Dairy systems in south-eastern Australia are inherently efficient due to their high levels of utilisation of homegrown forage (Dillon *et al.* 2005) and low cost of production. However, to maintain this natural competitive advantage, future dairy systems will need to adapt to a potential shortening of the spring but with an early to mid-spring forage surplus. Possible adaptations include changes in calving date, supplementary feeding, and earlier and more efficient conservation practices. Alternatively pasture and crop breeding efforts to delay reproductive development in spring will help alleviate the challenge of the spring forage surplus. This has been a continued focus of pasture improvement efforts in Australia and New Zealand with a range of cultivars readily avalible that have delayed reproductive growth (Lee *et al.* 2012). Despite the above mentioned challenges, dairy forage systems based on perennial and grazable forage speices have inherent cost advantages over those that are reliant on speices that require mechanical harvesting (Rawnsley et al. 2013). There is nothing in the modelling analysis presented in this paper that would suggest a change to this thinking, however, it is the subject of ongoing research.

In addition to the influence of climate change on the forage supply, it can be expected that there will be some agronomic adaption required, particularly within double cropping systems. This study indicated that silage harvests within a double cropping system typically occur earlier under the future climate scenarios in comparison to the climatic baseline. Slightly faster rates of maturity in grain sorghum, rice (*Oryza sativa* L.) and potatoes (*Solanum tuberosum* L.) (up to 6 days faster) due to increasing atmospheric CO_2 concentration have been observed in FACE experiments (Kimball *et al.* 2002). While this is consistent with the earlier harvest dates simulated for Dookie and Terang for forage sorghum, forage rape and maize, it is not enough to account for the shortening in maturity for maize of up to 4 weeks simulated at Elliott. The 1 or 2°C increase in temperatures under the future climate scenario resulted in more rapid phenological development due to faster accumulation of thermal heat units. Earlier silage harvests are an advantage within the double and triple cropping systems as one of the challenges to their success on-farm is the very short opportunity to establish successive crops (Garcia and Fulkerson 2005, Chapman *et al.* 2014). Under future climatic conditions, there should be a greater length of time available to ensure the successful establishment of crops in such systems.

The increase in total DM production within the irrigated forage systems under the future climate scenarios were associated with an increase in the irrigation requirement of these forage systems. The predicted decrease in annual rainfall (CSIRO and BOM 2015) is likely to have a relatively larger impact on irrigation water availability (Potter *et al.* 2010). This coupled with increasing competition for water resources means that the area of the farm allocated to irrigated forage systems may also decline. As such, while there may be an increase in the potential forage production per ha of these systems under the future climate scenarios, their production per farm may remain static or even decrease. This highlights that further research and systems modeling is required to consider external factors such as water availability and input prices when designing farming systems for the future. At Elliott, the DM yield increase of winter active lucerne under the +1/-10 scenario was less than the irrigated perennial ryegrass and the irrigation requirement either remained static or decreased. As a result, the winter active lucerne had a similar increase in WUE to that of irrigated perennial ryegrass. When grown with elevated atmospheric CO_2 concentrations lucerne exhibits a relatively large decrease in stomatal conductance with a concurrent increase in transpiration efficiency compared to other species (Wullschleger *et al.* 2002). In our modelling, this physiological response resulted in a decrease in irrigation water requirement and hence an increase in WUE. In regions where irrigation is limited by low availability and/or high water price, for example, Dookie in northern Victoria, forage options that have higher WUE than perennial pastures, such as annual pastures, lucerne and annual crops (Table 6) are likely to increase in use. These conclusions support the findings of agronomic studies in the region (Rogers et al. 2017).

In this study nitrogen fertiliser application rates were applied so that forage system yields were entirely responsive to the future climate scenarios. However, reducing the amount of nitrogen required to achieve profitable yields and the ability of species to take up nitrogen from urine patches is a growing considerations in selecting forage systems for dairy production. The former will be best served through selecting systems that include high yielding, nitrogen efficient crops like maize (Garcia et al. 2008). The latter consideration will be achieved through selecting forage systems that include speices that are actively growing over winter and early spring and can hence take up excess nitrogen from urine patches

(Malcolm et al. 2014). Nutritional composition of forages is also an important factor influencing the partitioning of nitrogen within the grazing animal (Chen et al. 2011) so is also an important consideration. The development of forage systems to reduce nitrogen losses from dairy farms will require ongoing research of which, modelling methodologies such as those applied in this study, will play a key role.

While the current study has evaluated a range of forage systems under potential future climate scenarios, the method of augmenting of historical daily climate data used in this study did not account for the predicted increase in extreme weather events (e.g. drought and heatwaves; Alexander and Arblaster 2009). These events would increase the chance of crop failure beyond that which is predicted in the current study. These risks will need to be considered alongside the productivity changes presented and discussed here.

The current study has identified possible changes in the forage systems utilised on dairy farms in south-eastern Australia under two potential future climate scenarios. In terms of annual DM yields, these systems appear relatively robust to future climate change scenarios. However, there were changes within these forage systems (e.g. proportion of yield from each crop, forgae growth patterns) that will have an impact on the farm system. While the physical implications of these changes have been documented, ultimately their implementation and adaptation of the farm system need to be considered within the context of their financial and whole of farm system effects.

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Conflict of Interest Statement

The authors declare no conflicts of interest.

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