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Economic impacts of climate change on the Australian dairy sector*

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We analyse the economic implications of climate-driven pressures on the pasture-based dairy sector in Australia. We use an integrated assessment model that includes a climate scenario generator, a climate-biophysical response framework and an economywide analytical framework. For the climate scenario generator, we use data from the OzClim database of the Commonwealth Scientific and Industrial Research Organisation. For the climate-biophysical response framework, we use the DairyMod model with inputs of changes in climate variables from OzClim to quantify climate change effects on pasture growth and productivity. For the economywide analytical framework, we use the National Integrated Assessment Model to quantify the economic implications of these effects on the dairy sector. The simulated pattern of regional changes in dairy output is not a simple function of the changes in dairy productivity. Our results show that the relative size of productivity changes across regions affects the relative competitive advantage of dairy-producing regions. Several factors affect the regional distribution of simulated dairy-output changes, including substitution among sources of dairy output and competition for inputs like supplementary feed. An increased output in regions with moderate reductions in dairy productivity may occur because the severely climate-affected regions absorb the greatest loss in output.

Key words: climate change, dairy farming, general equilibrium, greenhouse gasses, livestock.

1. Introduction

Pasture production is heavily reliant on the climate. Climate change scenarios indicate that shifts in climate, particularly changes in temperature and rainfall, increase the vulnerability of agricultural sectors. This includes the Australian dairy sector (Hennessy 2011). Pasture-based dairy systems rely on efficient conversion of pasture to milk. For example, stocking rates (cows/ha) and calving times are key management decisions used to align animal requirements with the seasonal pattern of pasture supply (see Macdonald

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et al. 2008; Chapman *et al*. 2009). Projected future climatic changes are likely to alter these patterns of pasture growth and thus require farmers to adapt their grazing systems (Cullen *et al*. 2009). We analyse the economic implications of climate-change-driven pressures on the pasture-based dairy sector in Australia. We focus on the south-eastern regions (i.e. Victoria, Tasmania and South Australia), which account for 80 per cent of Australia's milk output (Dairy Australia 2011a).

In the coming decades, climate change is likely to influence the dairy sector in several ways. First, this sector is largely dependent on rain-fed pasture systems (Dairy Australia 2009). Particularly in the southern and eastern states of Australia, climate change is likely to reduce the reliability of available water (Hennessy 2011), in turn reducing the ability of rain-fed pasture to support dairy herds. Second, climate shifts may contribute to adverse effects in dairy cattle, including stress-related illnesses, pests and diseases, all of which can potentially reduce dairy cattle productivity in Australia. For example, climate change can increase heat stress in livestock (Henry *et al*. 2012) and increase the incidence of cattle ticks (Preston and Jones 2006). Third, there is uncertainty about the effects of climate change in foreign dairy industries and their response to this issue in an already highly regulated market (Dairy Australia 2011b).

The Intergovernmental Panel on Climate Change (IPCC) designed a set of socio-economic scenarios to test solutions for climate-related issues. These scenario groups (A1, A2, B1 and B2) are designed to assess demographic, economic, technological and land-use issues and to test regional adaptation plans. The four groups are further divided into several unique scenarios for specific situations (IPCC 2007). Our main focus is the A1B scenario that suggests that south-eastern Australia will continue warming, up to 4°C, until the end of the 21st century, with annual rainfall projections ranging from −30 to +10 per cent, relative to the historical climate. Recent analysis (Holz *et al*. 2010; Cullen and Eckard 2011) of the impacts of future climate scenarios on pasture-based dairy production indicates considerable variation in projected output trends among different parts of south-eastern Australia. For example, higher production is projected in north-western Tasmania, which includes the dairy-producing region of Elliott. The cool-temperate climate in this region limits pasture production during the cooler months, but a warmer and drier future climate may sustain its viability (Holz *et al*. 2010; Cullen and Eckard 2011) by increasing pasture growth in the cooler months. In contrast, lower production is projected in the temperate regions of southern Victoria, which includes the dairy-producing regions of Terang and Ellinbank, due to a contraction of the spring growing season in warmer and drier future climates (Cullen *et al*. 2009).

We analyse the impact of changes in key climate variables, such as temperature and rainfall, on pasture growth and hence on stocking rates and output in key dairy-producing regions in south-eastern Australia. We use an integrated assessment-modelling framework that encompasses climate, bio-physical and economic interactions. We do not explicitly account for effects of climate change on other agricultural industries (except for the grains industries), other vulnerable areas (such as infrastructure) or foreign dairy producers, all of which may influence the overall impacts on Australian dairy producers.

2. Analytical framework and scenarios

Our analytical framework has three components: a climate scenario generator, a climate-biophysical response framework and an economywide analytical framework. Figure 1 schematically illustrates our analytical framework and the modelling process.

For the climate scenario generator, we use the OzClim framework of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (www.csiro.au/ozclim) (see CSIRO 2011). As shown in Figure 1, the OzClim framework generates temperature and rainfall changes, across a quarter degree grid, which corresponds to the selected IPCC emission scenarios.

For the climate-biophysical response framework, we use the DairyMod model (Johnson *et al.* 2008). DairyMod is a biophysical model that incorporates a pasture module and an animal module. It can be a useful tool for estimating pasture growth (Johnson *et al.* 2008). For example, DairyMod has been used to simulate pasture production, in response to

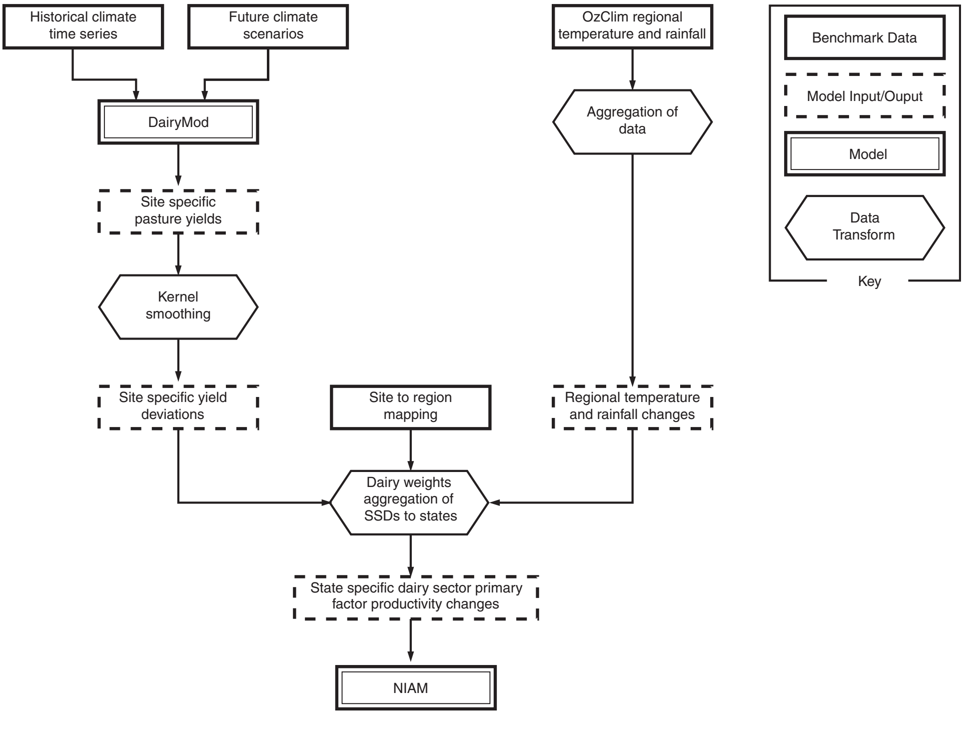

Figure 1 Analytical framework and modelling process.

climate variability, at various sites in eastern Australia (Cullen *et al.* 2008). It has been used to assess the effects of climate change projections for elevated CO_2 concentrations with warmer temperatures and reduced rainfall on pasture growth in south-eastern Australia (Cullen *et al.* 2009). It has also been used to quantify the potential impacts of climate change on pasture growth, dry matter yields, pasture intake by dairy stock, and hence on dairy stocking rates and milk output under alternative emission pathway scenarios in key dairy-producing regions in south-eastern Australia (Cullen *et al.* 2009; Cullen and Eckard 2011).

DairyMod uses information on weather/climate, water-holding capacity of soils, pasture species, livestock energy needs and grazing, fertiliser, and irrigation management practices. Inputs of weather/climate variables to the DairyMod include minimum and maximum temperature (°C), precipitation (mm), solar radiation (MJ/m^2), vapour pressure (kPa) and minimum and maximum relative humidity (%) (Cullen and Eckard 2011). We used historical climate data to create the DairyMod baseline. The data are perturbed uniformly for all future time periods by combining temperature and precipitation changes to create the DairyMod future scenarios. The DairyMod model generates pasture yields and a range of other model outputs that are specific to chosen sites in selected dairy-producing regions. We use the kernel-smoothing technique in our analytical framework. This technique represents the mean deviations from the baseline in site-specific pasture yields (corresponding to future climates) as a smooth function of temperature and precipitation deviations from the baseline climate.

The climate-biophysical response framework of OzClim plus DairyMod provided climate-change-induced changes in dairy productivity as inputs to the economywide framework used in our study (see Figure 1). OzClim generates climate change scenarios based on 23 global climate models. Furthermore, OzClim can combine a climate change scenario with the observed data sets to create a projected future climate. OzClim also maintains internal consistency when generating climate scenarios for multiple climatic variables. These features are particularly useful for generating inputs for impact assessments. For the baseline and future climate scenarios considered in this study, monthly projections for temperature (°C) and precipitation (% change of total monthly rainfall in mm) were obtained from OzClim.

For the economywide analytical framework, we used the National Integrated Assessment Model (NIAM) (see Hanslow 2010). NIAM is jointly developed by the Centre of Policy Studies at Monash University and CSIRO. It is based on the Monash Multi-Region Forecasting (MMRF) model (see Adams *et al.* 2008). MMRF has been used extensively in Australia, including an analysis of the Carbon Pollution Reduction Scheme (see Centre of Policy Studies 2008) and climate change impacts on the Australian economy (see Garnaut Climate Change Review 2008). In essence, NIAM is a dynamic multisectoral general equilibrium model of the Australian economy. NIAM can make projections for major economic sectors, after accounting for sectorwide and economywide production and consumption decisions and international trade.

We used a NIAM that allows for analysis across all Australian states and territories and 61 industries, each of which uses inputs of 64 commodities (domestically produced and/or imported) and 11 primary factors of production (land, capital and nine occupational categories of labour). The overall process comprised several steps, including the mapping of DairyMod sites and OzClim output to statistical subdivisions (SSDs), the calculation of pasture-yield changes for each SSD and the aggregation of these to state-level dairy productivity changes using SSD-level dairy production weights. SSDs are defined as socially and economically homogeneous regions (within states) that are characterised by identifiable links between the inhabitants.

In response to price changes or changes in technical efficiency, industries can substitute between inputs. For example, substitution between primary factors (land, capital and labour differentiated by broad occupational categories) allows changes in the capital intensity of production. Of particular relevance to our study is the substitution between the primary factors, 'land' and 'grains', as inputs to the livestock industries. This captures the possibility of purchasing supplementary feed as a substitute for pasture, which is represented by the primary factor land. The elasticity of substitution here is three and is based on the TERM-H2O model (Dixon *et al*. 2012). For example, input substitution possibilities permit the dairy sector to move to a more capital-intensive structure that uses less pasture and more supplementary feed. This dairy-sector climate change adaptation is noted in the Garnaut Climate Change Review (2008).

To earn the highest return, industries compete for primary factors that reallocate between industries. Within each state, land can reallocate between agricultural industries, to a limited extent. This reallocation occurs according to a constant elasticity of transformation frontier, with a low elasticity of 0.5 to capture the heterogeneity of land. The reallocation of capital between industries is flexible in the long run. In the short run, however, it is limited by industry-specific capital accumulation equations, so that industry capital stocks can change only gradually in response to investment reallocations towards industries with higher returns. In this way, the dynamic nature of the NIAM model facilitates a realistic adjustment path, while also accommodating the variation over time of the climate change effects analysed in this paper.

2.1. Scenario description

We analyse the following scenarios:

1. Reference case (baseline) scenario: a situation without climate change impacts;
2. Future 'moderate' climate scenario: impacts on dairy-sector productivity in pasture growth in south-eastern Australia under the IPCC A1B scenario. This scenario has three subscenarios:

2a. The impacts of climate-change-driven rainfall changes are assumed across dry-land pasture and irrigated-pasture systems (the latter based on an adjusted rainfall change for irrigated-pasture-based dairy) (labelled as 'IrrDiff' subscenario);
2b. Subscenario 2a plus changes in the use of feed supplements as an adaptation strategy for climate change (labelled as 'PlusFeed' subscenario).
2c. Subscenario 2b plus changes in the supply of feed supplements due to climate change impacts (labelled as 'SupFeed' subscenario); and

3. Future 'extreme' climate scenario: impacts on dairy-sector productivity in pasture growth, incorporating all the effects included in the IrrDiff, PlusFeed and SupFeed subscenarios, but consistent with the IPCC A1FI scenario.

According to Whetton (2011), in the IPCC A1B scenario, the best available estimate of annual average warming across Australia by 2030 (relative to 1990 temperature) is around 1°C. Warming estimates range between 0.7 and 0.9°C in coastal areas and between 1 and 1.2°C inland. Projected warming by 2050 varies from 0.8 to 1.8°C (under the 10th percentile of scenario A1B or under low greenhouse gas emission levels) and 1.5 to 2.8°C (under the 90th percentile of scenario A1B or under high greenhouse gas emission levels). Furthermore, there is likely to be less rainfall in southern regions of Australia, particularly in winter, and in southern and eastern regions in spring (Whetton 2011).

The A1B climate change scenario used in this study is described on the OzClim website (http://www.csiro.au/ozclim/presets.do) (CSIRO 2011) as a moderate-impact scenario over Australia as a whole. It is generated from the Global Climate Model developed by ECHAM5/MPI-OM (the Max Planck Institute-ocean model), in combination with a moderate rate of global warming and the A1B scenario. We refer to it as the A1B-moderate climate change scenario. This is the 'moderate' climate scenario 2 above. In contrast, the A1FI scenario used here is described on the OzClim website as a high-impact scenario in Australia with a high rate of global warming. It is generated from the Geophysical Fluid Dynamics Laboratory Coupled Model, version 2.1. This is the 'extreme' climate scenario 3 above.

We formulated our climate scenario analyses to capture several important aspects. First, we assessed potential impacts of climate change on dry-land pasture production and implications for dairy output. Second, we allowed supplementary feeding of dairy stock as an adaptation strategy for climate change. Third, we incorporated the overall potential changes of supplementary feed on Australia's grains industry sector, based on the estimated impact functions from the analysis provided by the Garnaut Climate Change Review (2008). Fourth, we simulated the overall potential effects of an extreme climate change scenario (i.e. scenario A1FI), in which Australia is projected to warm rapidly with very large and rapid increases in global greenhouse gas concentrations through the 21st century.

In assessing climate change impacts for dairy systems that depend on irrigated-pasture systems, we allowed for changes in irrigation water availability, or run-off, under the assumed climate change scenario. We adjusted the change in precipitation estimates from the OzClim database to represent the presence of irrigated dairy production, which depends on run-off more than rainfall. Our adjustments were based on Australian Bureau of Statistics (ABS) (2011) data for irrigated dairy production in total dairy output and the findings of Chiew and McMahon (2002), who use hydrologic modelling to estimate climate change impacts on run-off in Australia. They find that run-off (and therefore irrigation water availability) will decline at three times the rate of rainfall (i.e. a five per cent rainfall reduction will lead to a 15 per cent run-off reduction) and that pasture production will decline at a rate equivalent to 1 tDM (dry matter) per ha, for a reduction of 1 ML irrigation applied per ha (industry average; Rawnsley *et al.* 2009). In wet and temperate catchment areas, the percentage change in run-off is estimated to be twice the percentage change in rainfall. In ephemeral catchment areas, the percentage change in run-off is estimated to be more than four times the percentage change in rainfall. Furthermore, according to a 2008 CSIRO analysis of rainfall run-off within the Murray-Darling Basin, the median reduction in surface water availability by 2030 is estimated to be around 11 per cent, relative to what it would be without climate change. The reduction is expected to be greatest in the south–east, where the majority of the run-off is generated and where the impacts of climate change are projected to be greatest (CSIRO 2008).

Raising the capacity of water storage may help address the reduced water availability for agriculture. According to Commonwealth Scientific and Industrial Research Organisation (CSIRO) (2008), the current capacity of farm dams across the Murray-Darling Basin is estimated to be around 2,000 GL. Projections based on historical trends in farm dam growth, and current policy settings indicate that total farm dam capacity may increase by 10 per cent by 2030. However, new farm dams will likely reduce average annual run-off by only about 0.7 per cent across the Murray-Darling Basin CSIRO 2008).

The dairy-producing regions in south-eastern Australia were represented in our analysis using detailed biophysical simulation with DairyMod, under historical and alternative future climates, for specific locations or experimental sites in key dairy-producing states. Table 1 lists the sites, which were selected because they represent a spectrum of climatic zones and soil types typical of the dairy production sector in south-eastern Australia (Cullen and Eckard 2011).

Our DairyMod analysis extended the approach used in Cullen *et al.* (2012) to other sites. Dairy-grazing systems for each of the chosen sites (Table 1)

Table 1 Descriptions of the sites simulated in DairyMod

Site	Soil type	Climate	Rainfall (mm)*	Irrigated or rain-fed	Pasture species†	Dairy region
Mutdapilly	Black vertosol	Subtropical	836	Irrigated	ARG, kikuyu	Queensland
Camden	Brown chromosol	Subhumid	752	Irrigated	ARG, kikuyu	New South Wales
Kyabram	Red-brown chromosol	Mediterranean	450	Irrigated	PRG, WC, paspalum	Northern Victoria
Mt Gambier	Calcarosol	Temperate	733	Rain-fed	PRG, WC	South Australia
Terang	Brown chromosol	Temperate	771	Rain-fed	PRG, WC	South-west Victoria
Ellinbank	Red mesotrophic haplic ferrosol	Temperate	1033	Rain-fed	PRG, WC	Gippsland
Elliott	Red mesotrophic haplic ferrosol	Cool temperate	1245	Rain-fed	PRG, WC	Tasmania

*Mean annual rainfall (1971–2010).
†PRG, perennial ryegrass, ARG, annual ryegrass, WC, white clover.

were simulated with DairyMod by using a baseline historical (1971–2008) climate data and alternative future climates. The alternative future climates covered a range of climate change possibilities, defined by a grid of temperature and precipitation variations. The future climates were generated by applying changes of 0, 1, 2, 3 or 4°C to maximum and minimum daily temperatures (with corresponding atmospheric CO_2 concentrations of 380, 435, 535, 640 and 750 ppm, respectively) and by applying rainfall changes of −30,−20,−10, 0 or +10 per cent.[1] For the baseline and each alternative future climate, we used DairyMod to simulate pasture yield for all chosen sites. For each site, we calculated climate configurations, year of climate data and total annual pasture production (t DM/ha). Table 2 presents the changes in seasonal rainfall and temperature for each region and for each future climate subscenario.

Annual yields were expressed as deviations relative to corresponding baseline pasture yields. The means of these deviations across all years were calculated, and a kernel-smoothing technique was used to interpolate between the 25 points of the discrete grid defined by the five temperature and five precipitation variations. For rain-fed sites, the mean deviation in pasture yield from baseline yields was represented as a smooth function of temperature and precipitation deviations from the baseline climate. For irrigated sites, it was represented as temperature and total water input deviations. These smooth summary functions of DairyMod results were

[1] Zero change in both temperature and precipitation represents the baseline climate.

Table 2 Temperature, rainfall and productivity changes in 2050, relative to baseline

	Temperature change °C		% change in rainfall/irrigation water applied in modelling				% change in average state dairy-sector primary factor productivity	
	Scenario 2	Scenario 3	To rain for scenario 2	To irrigation for scenario 2	To rain for scenario 3	To irrigation for scenario 3	Scenario 2	Scenario 3
New South Wales	1.2	1.9	−6.7	−26.2	−24.7	−61.8	−18.1	−33.0
Victoria	0.9	1.5	−6.6	−26.7	−17.5	−51.9	−9.8	−23.1
Queensland	1.2	2.1	−6.4	−27.9	−36.4	−77.6	−26.1	−53.4
South Australia	0.7	1.4	−7.3	−26.6	−34.7	−69.4	−11.2	−24.9
Tasmania	0.7	1.2	−3.4	−12.0	−8.4	−28.4	1.4	−6.7

Note: Scenario 2 is the moderate scenario (under A1B) and includes the three subscenarios (2a), (2b) and (2c) or IrrDiff, PlusFeed and SupFeed, respectively. Scenario 3 is the extreme scenario (under A1FI). Temperature and precipitation changes are dairy-production-weighted averages over statistical subdivisions. They are not direct model inputs, but useful indicators of climatic conditions.

required, since temperature and precipitation changes from OzClim were between the discrete set of temperature and precipitation variations used for the DairyMod future climates.

Sites simulated with DairyMod were associated with SSDs based on geographic proximity. Temperature and precipitation changes from OzClim for a latitude and longitude grid were likewise aggregated to an SSD. Small (typically urban) SSDs that contained no grid points were assigned climate characteristics of the closest nonempty SSD. OzClim provided temperature and precipitation changes for 2020, 2030, 2040 and 2050. Values for intervening years were obtained by linear interpolation. In this way, annual climate change impacts on pasture yields were calculated at an SSD-level, and a state-level value was calculated as a dairy-production-weighted average. This drew upon the dairy production data in the detailed database of the MMRF and TERM models (Horridge 2012).

DairyMod focuses on a single sector, so there was no treatment of the rest of the economy. It is common to assume that prices are fixed in such models. However, the trend in food prices (including the prices of dairy products) has increased over the past decade. Just over 40 per cent of annual milk output in Australia is exported in the form of various processed products. The increase in income and population growth in rapidly growing Asian economies is likely to continue to raise future demand for Australian dairy exports (Dairy Australia 2012). This demand is likely to incentivise Australian dairy producers to continue to adjust to climate-change-driven pressures and enhance their productivity. Current adjustments, for climate change and subsequent rising demand, include increased pasture productivity and targeted supplementary feeding (Dharma *et al.* 2012). The ‘PlusFeed’ and ‘SupFeed’ subscenarios in this study captured some of these adjustment effects (e.g. the use of feed supplements).

DairyMod allowed us to analyse the biophysical impacts of climatic changes on dairy production. In particular, DairyMod enabled us to analyse the links between projected climatic changes and pasture production in the major dairy regions of eastern Australia. The approach developed in this study was to use the change in pasture production in a future climate scenario, relative to the historical climate for the location, as a predictor of change in milk production for dairy regions.

We based our rationale for this approach on the tight linkage between pastures and milk production in the Australian dairy industry. Several factors support this link. First, forage comprises 70–75 per cent of cattle feed requirements in the dairy industry (Dairy Australia 2012). Second, there is a strong positive correlation between annual pasture production and the stocking rate (cows/ha) of dairy herds (Chapman *et al.* 2009). Third, analysis based on Australian Dairy Industry Survey undertaken by ABARES over the past several decades points to a strong positive relationship between stocking rates and milk production (see Dahl *et al.* 2013). Finally, we assume that a strong relationship between pasture consumption and milk production will continue. This assumption is based on the close relationship between farm profitability and the amount of pasture DM consumed, given the relatively low cost of pasture as a key source of feed (Chapman *et al.* 2009). In recent years, pasture costs ranged from \$100 to \$150/t DM, compared to the price of feed supplements, which ranged between \$280 and \$350/t (see Armstrong *et al.* 2010; Ozkan *et al.* 2012).

An alternative biophysical modelling approach directly simulates farm milk production in the climate scenarios using DairyMod. We deemed this approach infeasible in this study, because of the difficulties in scaling up simulations from the farm to regional level. These difficulties included the ability for DairyMod to capture variability across farms within and between regions in climate, soil, pasture species, stocking rate, feeding strategies, management skill and so on. For these reasons, we chose the simpler approach of linking changes in pasture production to changes in regional milk output. We used changes in pasture yields from DairyMod (as a measure of dairy-sector productivity) to inform changes to dairy-sector primary factor productivity in NIAM. Following the procedure adopted in the Garnaut Climate Change Review (2008), percentage changes in pasture yields were represented in NIAM as percentage changes in dairy-sector primary factor productivity (see Table 2).

3. Results and discussion

Figure 2 shows estimated changes in the value of dairy output in south-eastern dairy-producing regions and at the national level under the future climate scenarios, relative to the baseline. These changes were adjusted to 2009–2010 currency rates and were calculated as per cent changes in scenario output (relative to the baseline) times the 2009–2010 gross value of dairy production (see ABS 2011). Figure 3 illustrates the relationship between dairy output, productivity and land for the selected climate change scenarios.

3.1. Production effects

Several key points emerge from the results shown in Figure 2. First, results for national dairy output across scenarios and years conformed to expected results, based on the magnitudes of both dairy and nondairy productivity changes and adaptation measures. For 2020, 2030, 2040 and 2050, respectively, the per cent deviations of national dairy output from baseline levels were −0.7, −1.3, −2.2 and −3.3 in the IrrDiff scenario. They increased to −0.5, −1.0, −1.7 and −2.5 in the PlusFeed scenario (when supplementary feeding was allowed). They decreased to −0.6, −1.1, −1.9 and −2.9 in the SupFeed scenario (when climate change effects on the NIAM grains-sector reduced the supply of supplementary feed).

Second, the pattern of change in output across scenarios and years at the national level did not prevail at the state level, except in Victoria. This

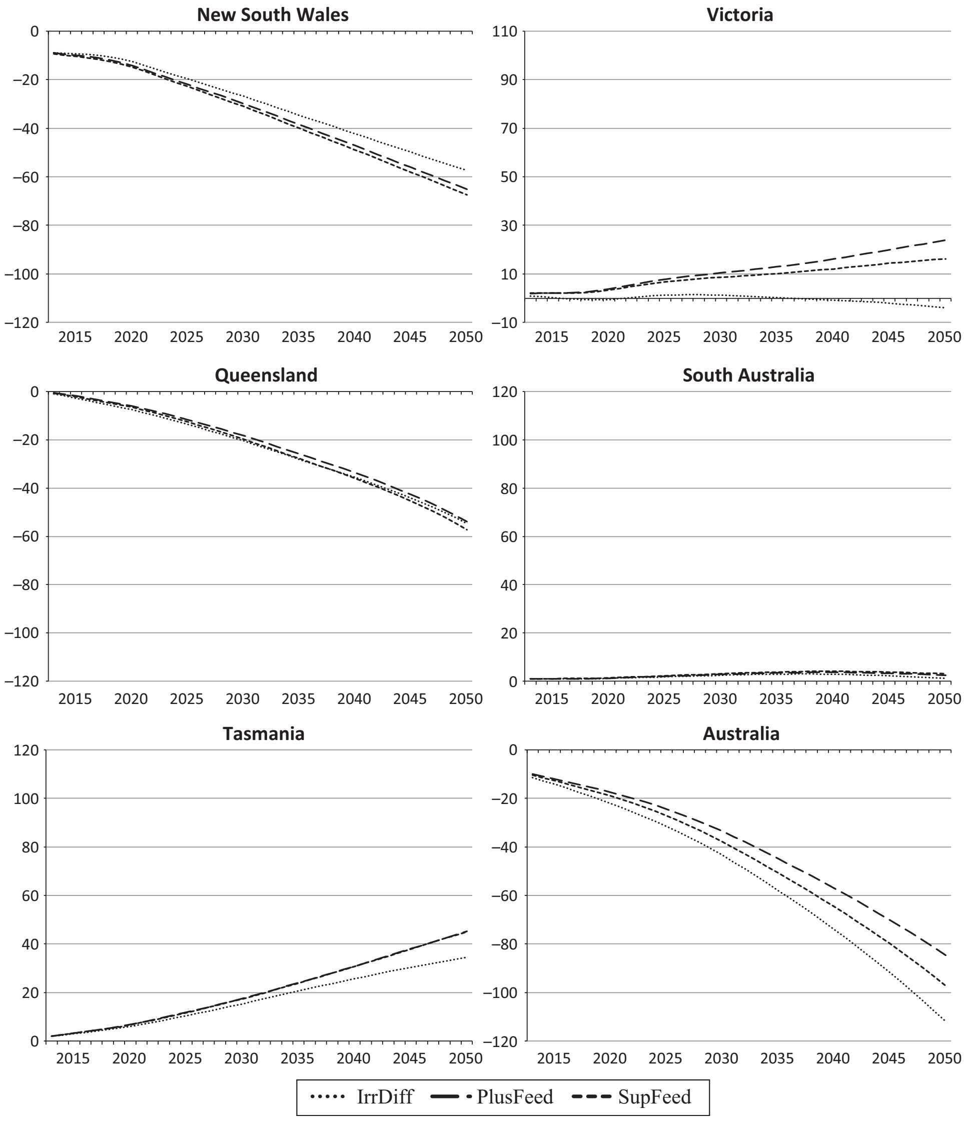

Figure 2 Changes in value of dairy output (2009–2010; $ m) under future climate scenarios, compared to baseline (Calculated as per cent changes in scenario output [relative to the baseline] times 2009–2010 gross value of dairy production [ABS 2011]).

was because state-level dairy output was influenced by state-specific productivity levels and by other states' price-induced supply reallocation between states. For example, the lowest dairy output for Victoria and Tasmania, as well as for Australia as a whole, occurred in the IrrDiff scenario. For New South Wales (NSW), however, the highest dairy output occurred in the IrrDiff scenario, mainly because of the relatively more adverse impacts in Victoria and Tasmania and therefore supply shifting towards NSW.

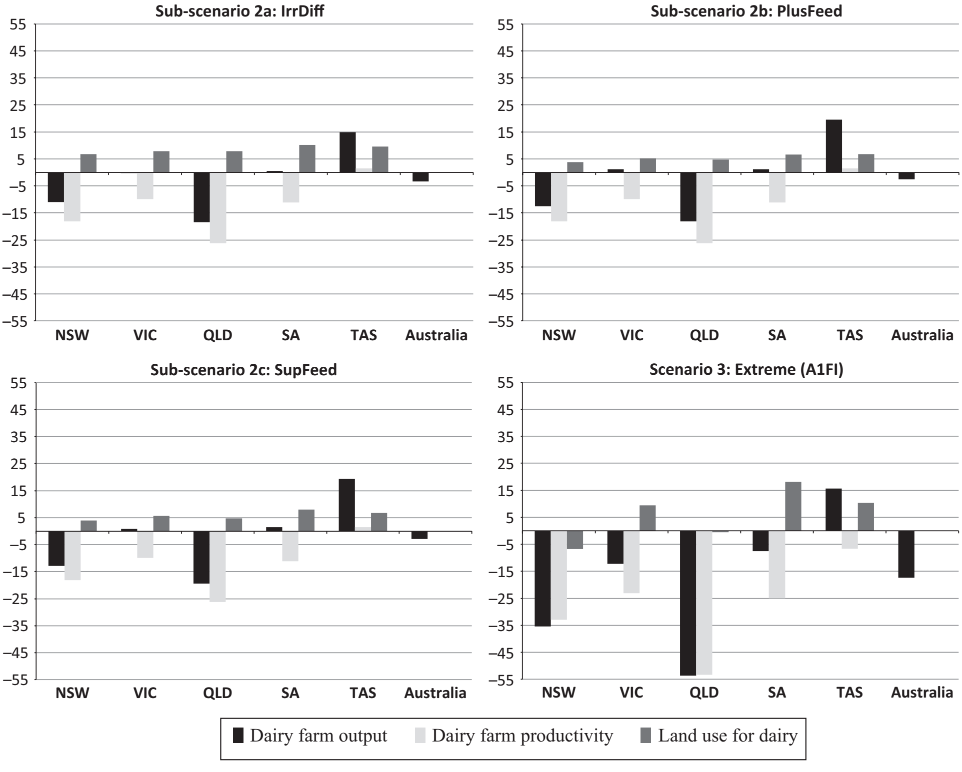

Figure 3 Dairy production, productivity and land use: Changes (%) in 2050 under future climate scenarios, compared to baseline.

Third, the inclusion of supplementary feeding in subscenarios PlusFeed and SupFeed was not uniformly advantageous, relative to IrrDiff, for all states. Dairy output was lower in NSW under PlusFeed and SupFeed than under IrrDiff. This was attributable to competition for supplementary feed between dairy-producing states and the allocation of feed towards the lower cost producer.

Fourth, dairy production in Tasmania was estimated to continue increasing, relative to what it would be otherwise, in the presence of assumed climatic changes. We observed this result during the simulated period (2013–2050), even in the extreme A1FI scenario (see Figure 3) and even though dairy productivity declined (see Table 2). Tasmania experienced much less productivity decline than did other states. Again, in the A1FI scenario, cost-induced substitution across dairy output from different sources showed a significant effect.

The results illustrate the effects of embedding dairy-sector productivity changes, implied by the linking of DairyMod and OzClim climate scenarios, in the economywide NIAM model. At the national level, there was a plausible and intuitive ordering of results, which was not preserved at the state level because of supply reallocation of dairy farm output in response to relative competitive pressures and because of competition for resources (such as supplementary feed) between dairy producers.

3.2. Substitution effects

Dairy activity also competed for land with other agricultural activities in the same region. Land use increased in all A1B climate change scenarios in all regions, regardless of whether output or productivity decreased or increased (see Figure 3). These results arose from two sources: relatively inelastic demand for dairy farm output and the substitutability between dairy outputs from different states. Recall that dairy output refers to dairy farm output, the demand elasticity for which is much lower than for final dairy products, because of the value-adding that occurs between farm gate and final consumer.

Inelastic demand means that the productivity-induced change in the dairy price had a less proportional effect on dairy output than did productivity change. Hence, for a productivity decline, more land was required to produce a lower level of output. However, in Tasmania, the substitution among dairy outputs from different sources offset the decline. For a sufficiently large gap between dairy productivity, there was scope for significant switching to dairy in Tasmania from dairy in the other states. In the supplementary feeding scenarios, land use decreased everywhere except South Australia, where substitution between land (pasture) and grains (purchased feed supplements) offset the decrease. However, in the A1FI scenario, where national decreases in dairy output were much larger than in the A1B subscenarios, output for some states (e.g. NSW, Queensland) declined by a sufficiently large amount and caused a decrease in land use. As the productivity effects indicate, these states were most adversely affected by the extreme climate change under A1FI.

Finally, Figure 4 illustrates how change in dairy output cannot be inferred simply from the size of productivity changes. It also highlights the importance of considering climate change impacts on dairy in a broader economic context. Figure 4 graphs per cent deviations from baseline in dairy output for all states, years and scenario 2 against the corresponding productivity changes. In a simple relationship between output and productivity, the points cluster tightly around an upward sloping curve. However, the points in our results appeared along three different types of relationships. Tasmania, in particular, showed a much stronger (steeper upward sloping) relationship between output and productivity that was underpinned by the previously discussed mechanism of price-induced substitution. The Victoria and South Australia data points exhibited weak, even counterintuitive, relationships between output and productivity. Again, cost-induced substitution and the positioning of data points in the middle of the range of productivity changes counteracted the tendency of productivity declines considered in isolation.

Our analysis shares some similarities with other studies. For example, the predominantly pasture-based New Zealand dairy industry is estimated to experience a 2.8 to 4.3 per cent decline in milk production by 2030 due to

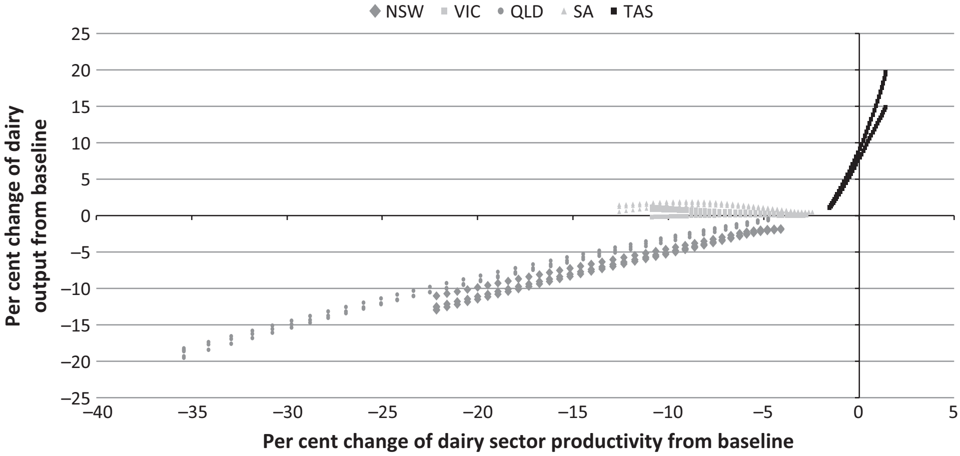

Figure 4 Dairy output versus dairy productivity: Changes (%) under future climate scenario 2 (A1B) for regions of south-eastern Australia and for all time periods.

climate change (Wratt *et al*. 2008). In Central Europe, pasture-based dairy systems are projected to suffer from reduced rainfall and variations in pasture yields over the next four decades (Trnka *et al*. 2009). Higher temperatures in the coming decades in north-eastern United States are projected to have a substantial potential negative impact on milk production (Wolfe *et al*. 2008). In the south-eastern United States, the effect of heat stress caused by global warming is estimated to have a significant nonlinear negative effect on milk production (Mukherjee *et al*. 2012).

4. Concluding remarks

Australian dairy production may face increasing challenges in the coming decades because of the potential adverse impacts of climate variability and change. According to Cullen *et al*. (2009), pasture production in Mediterranean and temperate climates may increase slightly with moderate changes in temperature and rainfall (e.g. up to 1°C warming and a 10 per cent decline in rainfall). However, with further warming and rainfall reductions, annual pasture production is projected to decline, because higher winter and early spring pasture-growth rates will be offset by a shorter spring growing season. On the other hand, cool-temperate environments appear to be more resilient to these climatic changes (Cullen *et al*. 2009).

Dairy production on irrigated pastures is also likely to be affected by future climate changes, as water requirements increase and water availability decreases. Warmer and drier climates in south-eastern Australia will adversely affect pasture-based dairy systems in Australia (Cullen and Eckard 2011). Some adaptation strategies to sustain continuing production include increasing the amount of grain or dietary oils in feed (Eckard *et al*. 2010) or changing the forage base to deep-rooted and heat-tolerant grasses (Howden *et al*. 2008; Cullen *et al*. 2009).

Our analysis also indicates that regional differences in dairy production will arise from the relative magnitudes of regional climate change effects. These effects influence the relative competitive advantage of different regions, with respect to both the supply of dairy output and purchases of inputs, such as supplementary feed. Anticipated climate change impacts on dairy productivity alone are not enough to infer likely changes in the distribution of dairy production in a straightforward way.

Our simulation results for changes in national dairy output are quite modest, from the perspective of overall aggregate production in the A1B scenario. However, much higher levels of warming and drier conditions in the A1FI scenario may have considerable potential adverse impacts on the Australian dairy industry. Our analysis indicates that, by 2050, the loss in dairy output will be six times larger in the severe A1FI scenario than it would be in the moderate A1B scenario.

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