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Climate Change Adaptation in the Southern Australian Livestock Industries

(CSIRO component)

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Abstract

This project was funded by MLA and the Australian Government to develop information about the likely extent of climate change – and options for adaptation to it – as it will affect livestock producers in southern Australia. Mathematical modelling is the only viable approach to this challenge. A set of modelling analyses were carried out using the GRAZPLAN simulation models of pasture and livestock production to explore the impacts of projected future climates and opportunities to adapt to them.

Our results indicate that there is a real prospect of 15-20% overall reductions in pasture growth across southern Australia by 2030 in the absence of adaptation; reductions in profitability will be larger again. Climate change impacts are likely to be most severe in the lower-rainfall parts of the cereal-livestock zone. No single alteration to management will be a "silver bullet" in response to climate change, but combinations of adaptations can probably be found to maintain the productivity of livestock production across southern Australia to 2030. By 2050 and 2070, on the other hand, it is likely that new technologies or systems will need to be found if livestock production at the dry edge of the farming zone is to remain viable.

Executive summary

Sheep and cattle producers who intend to remain in the industry over the next 20-40 years need to understand the extent of changes to productivity that may result from climate change, and the options available to adapt to changing climates. This project was part of *Southern Livestock Adaptation 2030*, a program of research, development and extension into adaptation options for southern Australian livestock producers that formed part of the Australian Government's *Climate Change Research Program*. A key feature of *Southern Livestock Adaptation 2030* has been collaboration between research organizations (including CSIRO) and State government extension agencies from all 5 states in southern Australia.

In this project we used the GRAZPLAN simulation models of pasture and livestock production to explore a variety of issues relating to climate change. The centrepiece of our research was an analysis of livestock production systems for all combinations of 25 locations that are representative of southern Australia, 5 livestock enterprises, 3 future dates (2030, 2050 and 2070), 4 different projected global climates and 9 adaptive changes to management or genetics (singly and in combinations). No comparable study has been attempted worldwide for any agricultural industry.

Despite the enormous complexity of our research question, a set of key messages emerges from the mass of modelling results:

- In the absence of adaptation, the magnitude of climate change impacts will be large; the potential exists for a significant decrease in the total value of livestock production.
- Based on the available projections, there is a real prospect of 15-20% overall reductions in pasture growth by 2030 in the absence of adaptation.
- Declines in production and profitability can be expected to be significantly larger than declines in total pasture growth. This differential is caused by the need to leave herbage unconsumed to protect the soil resource, and is probably exacerbated by increased variability in future climates.
- Climate change impacts, and hence the need for adaptive responses, are greatest in the lower-rainfall parts of the cereal-livestock zone and tend to be less severe in the south-eastern parts of the high-rainfall zone.

- Taken across southern Australia, all broadacre livestock enterprises are likely to be strongly affected by projected future climates. It appears that impacts on beef breeding will be somewhat smaller in relative terms than the impacts on other enterprise types; these differences are unlikely to be large enough to make beef cattle more economically attractive than other enterprises, however.
- The uncertainty associated with these projected changes in livestock production is large – and is caused by uncertainty in rainfall projections – but the above trends are discernable nonetheless.
- A range of different adaptations, based on currently-available technologies, are potentially effective in ameliorating the impacts of projected climate changes. The most important of these are:
  - increasing soil fertility, so increasing the water use efficiency of pasture growth;
  - ongoing genetic improvement of livestock;
  - introduction or increased use of summer-active perennials (particularly lucerne);
  - in some locations, the use of confinement feeding to protect ground cover.
- No single adaptation will be completely effective adapting the broadacre livestock industries to climate change. In most situations, a combination of adaptive responses will be required.
- It is likely that in 2030, combinations of adaptations can be found to return most livestock production systems to profitability. By 2050 and 2070, on the other hand, our findings suggest that the lower-rainfall parts of the cereal-livestock zone will require either new technologies, a complete re-thinking of the feedbase or else sustained product price increases in order for livestock production to remain viable.

An important conclusion is that there are changes to management – in particular management for increased soil fertility and the adoption of systematic genetic improvement of flocks and herds – that are (i) likely to be sound adaptations to changing climates, (ii) need to be carried out over the long term and (iii) are likely to be sound investments in the present-day climate. The case for these adaptations should therefore be made by industry bodies with renewed force.

This project played a vital “back-office” role in ensuring that the *Southern Livestock Adaptation 2030* met its overall target communication target of 10,000 producers aware of findings relating to local climate change impacts and adaptation options. Within our project, our primary objective was to develop credible and consistent information about climate change impacts: this information is of particular relevance to industry bodies and policymakers. It has been disseminated through two workshops with industry and government stakeholders and through scientific publications, and will be made available to the public via a program website.

An intended side-effect of this project was to increase the capacity of the livestock industries to make use of modelling to address a range of issues into the future. We did this by extending the GRAZPLAN models to apply to C_4 native perennial grasslands, developing a set of representative grazing systems models that can be re-used to analyse a wide range of different R&D questions, and by training and building the confidence of a network of staff (across multiple organizations and states) who can apply models to RD&E activities. Finding – and funding – opportunities to allow this network of people to put their skills to good use is an important next step arising from *Southern Livestock Adaptation 2030*.

The results of this project could contribute directly to a national assessment of climate impacts and the benefits of effective adaptation in Australia’s primary industries.

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Background

Sheep and cattle producers who intend to remain in the industry over the next 20-40 years need to understand the extent of changes to productivity that may result from climate change. Uncertainty about these changes limits the ability of producers – and other stakeholders in the industry – to plan for the long term. The main kinds of adaptation that livestock producers can make to new circumstances are to alter the proportional mix of livestock enterprises; change the management within each enterprise (key “profit drivers” here include stocking rate, mating date, timing of livestock sales and supplementary feeding policy); better match the genotype of their sheep and cattle to the new situation; or alter the pasture base, by sowing different pasture species or altering fertilizer regimes.

The Australian Government’s *Climate Change Research Program* (CCRP) was instituted in 2009 to help prepare Australia’s primary industries for climate change and build the resilience of the Australian agricultural sector into the future. One element of CCRP has research into options for producers to adapt to unavoidable climate change. The project described in this report is CSIRO’s contribution to *Southern Livestock Adaptation 2030*, a program of research, development and extension into adaptation options for livestock producers that has been funded by the CCRP and by industry (Meat and Livestock Australia, Dairy Australia and Australian Wool Innovation). A key feature of *Southern Livestock Adaptation 2030* has been collaboration between CSIRO, the University of Melbourne, the Tasmanian Institute of Agriculture and Government agencies from all 5 states in southern Australia.

Project Objectives

In conjunction with other projects in the *Southern Livestock Adaptation 2030* program:

1. By 2011, a knowledge base will be established to underpin ongoing engagement with broadacre livestock producers, and to facilitate further research, development and extension in climate change adaptation.
2. By 2011, 10,000 livestock producers across southern Australia will be aware of the key research outcomes of the program through a combination of field days, workshops and written material.
3. By 2011, a program of on-farm trialling of key recommendations within each of the agro-climatic regions of southern Australia will be defined, for implementation during the period 2012-2015 via the MLA Producer Demonstration Sites (PDS) program and similar programs supported by other RDE providers.
4. An improved modelling capacity will be established across a range of industry RD&E providers that will assist industry in evaluating adaptation options in more detail across a range of agro-climatic regions.

Methodology

<u>Simulation of grazing systems – the GRAZPLAN models</u>

Experimental investigation of the likely effects of changing climates is extremely difficult and expensive, in particular because of the expense of enriching atmospheric carbon dioxide (CO_2) concentrations and manipulating factors such as rainfall and temperature over large areas. When there is also a requirement to develop an understanding of climate change impacts across many regions and different production systems, mathematical modelling becomes the only viable approach to the research questions. The GRAZPLAN models (www.grazplan.csiro.au) have therefore been used extensively in this project. GRAZPLAN is a set of daily time-step simulation models of the dynamics of grazed temperate grasslands that is widely employed within Australia for purposes of research (e.g. Cayley et al. 1999; Clark et al. 2003; Mokany et al. 2010) and also in decision support for producers (Donnelly et al. 2002 and references therein; Moore 2005; Warn et al. 2006).

The GRAZPLAN models are driven by daily weather data. Equations describing the key processes of pasture and ruminant growth are cast in physiological terms and are expressed in a generic fashion, so that the model can represent a wide variety of grassland plants and animal breeds. The pasture model responds to the main environmental conditions that are expected to alter under changing climates: rainfall amount and pattern, temperature and atmospheric CO_2 concentration. The ruminant model predicts production of meat, wool and milk. Equations describing livestock intake allow for selective grazing of forage, and also for substitution between forage and supplementary feeds. The fate of the metabolizable energy, rumen-degradable protein and rumen-undegradable protein in animals' intake is followed and their use for maintenance, pregnancy, lactation, wool growth and change in body weight computed using the equations of the Australian feeding standard (CSIRO 2007). The ruminant model predicts animals' responses to changes in climate (to temperature in particular). Methane emissions by livestock are predicted with a modified form of the equation of Blaxter & Clapperton (1965). In most – but not all – of the studies reported here, we used the GrassGro decision support tool (Moore et al. 1997). The GrassGro software adds a flexible scheme for the management of grazing systems and simple financial analyses to the GRAZPLAN models.

An earlier study (Alcock et al. 2010) identified increased climatic variability, leading to greater risk of low ground cover and so of soil erosion, as a key factor limiting livestock production under climates projected for 2030. Accordingly, in the work reported here the concept of an "optimal sustainable stocking rate" has been used: the stocking rate which maximises long-term average profit of a given grazing system, subject to a constraint that the frequency of low ground cover should remain below a threshold value.

Downscaling future climates into local weather

Predictions of future climate change resulting from emissions of greenhouse gases are derived using physical models of the atmosphere, known as global circulation models (GCMs). These models are designed to provide insight into the behaviour of the atmosphere at large spatial and temporal scales. Agricultural simulation models such as GRAZPLAN require daily sequences of weather data as inputs. To examine the impact of alterations in climate at different locations, it is necessary to convert the changes in climate into sequences of daily weather values that realistically capture the important changes in the climate at a particular place. This process is known as "downscaling".

In this project, daily weather data sequences for a range of projected climates and locations have been constructed using a downscaling technique adapted from that of Zhang (2007). In order to take account of the uncertainty in projected climates, climate predictions from four global circulation models (GCMs) have been downscaled and used in modelling analyses: UKMO-HadGEM1 (Johns *et al.* 2006), CCSM3 (Collins *et al.* 2006), ECHAM5/MPI-OM (Roeckner *et al.* 2003) and GFDL-CM2.1 (Delworth *et al.* 2006). ISAM reference time courses of atmospheric CO_2 concentrations (Houghton *et al.* 2001) have been used in conjunction with these downscaled weather data.

Climate change impacts – exploration of the issues

Literature reviews

A review of prior work relating to adaptation of southern Australian livestock production to climate change was carried out and circulated to CCASALI program participants (Appendix 1). The review covered previous overview articles published on the subject, experimental studies and 3 earlier modelling studies. A set of research questions was derived from this information and presented to the wider CCASALI program team. Feedback on the research questions from state-based project leaders, modelling research project members and the program steering committee was then used to develop the operational plan for the rest of the project.

A second literature review was completed during 2010 by Drs Bob Godfree & Richard Culvenor that examined the potential for species in southern Australian pastures to evolve in response to climate change (Appendix 2).

Adaptations for shorter growing seasons

Our literature review made it clear that under the most likely scenarios, pasture growth in southern Australia will be characterised by shorter growing seasons with higher winter growth rates. We therefore carried out a preliminary simulation study with GrassGro that explored management options that might be adopted by managers of sheep enterprises in order to adapt to shorter, more intense growing seasons (Appendix 3). We constructed artificial weather records for 7 locations in which total annual rainfall and year-to-year variability of rainfall were the same but growing seasons were shorter. Average temperatures were increased by 2^oC and an atmospheric CO_2 concentration of 450 ppm was assumed, so increasing plant development, winter growth and evaporation rates. The long-term average profitability of a ewe enterprise producing first-cross lambs was then compared for each location under historical climate and shorter growing seasons, with and without (i) confinement feeding in summers with low ground cover; (ii) earlier and later age at first mating; (iii) earlier mating (November vs December); and (iv) addition of an early-flowering annual grass to the pasture; and (v) increased soil fertility.

Will managing for climate variability also manage for climate change?

In writing about policy options for climate change adaptation in agriculture, Pannell (2010) argued that farmers faced with a changing climate will successfully adapt their systems by means of successive small, short-term changes in management practice. His argument depends on two assumptions: first, that the feasible rate of on-farm practice change is greater than the rate at which changing climate will alter the production environment; and second, that farmers' perceptions of current conditions will be sufficiently accurate to allow them to adjust their management strategies.

To investigate these assumptions, a modelling study of adaptation policies under changing climates was carried out for a dual-purpose Merino ewe production system based on annual pastures at Lucindale, South Australia. The evolution of the model grazing system was simulated under changing climates from 2010 to 2099 that were projected by 2 GCMs for the SRES A1B emissions scenario, when each of four policies for progressively adapting stocking rate and joining date was followed:

- a "traditionalist" policy, i.e. maintain the optimal stocking rate and joining date from the 1970-2009 period.
- an "incremental" policy: make a small change in either stocking rate or joining date each year, based on relative profitability over the last 5 years.
- a "step-change" policy: every 15 years, choose the stocking rate & joining time that optimized net profit over the previous 15 years.

- a "forecast" policy: set stocking rate & joining time each year based on forecast long-term expected pasture production.

Novel features of this analysis included modelling grazing systems faced with changing climates (rather than multiple years of weather drawn from a single projected climate); analysis of small ensembles of realizations of the two GCM-projected climates; and the development of stochastic price sequences that allowed price as well as business risks to be taken into account.

Medium-term climatic variability and its effects on pasture and livestock production

At the commencement of this project in 2009, southern Australia had just emerged from the "Millennium Drought" – an extended period of dry conditions in Southern Australia. It was clear at the time that this drought had significantly affected the productivity and livelihoods of livestock producers. It was not clear, however, whether this long drought was a consequence of "normal" medium-term climatic variation or whether it was a unique event.

To explore this question, we used the GRAZPLAN grassland simulation models to simulate livestock production from representative grazing enterprises at 25 locations (see below) over seven 16-year periods starting with 1899-1914 and ending with 1995-2010 (Appendix 5). CO_2 concentrations of 350ppm were assumed. At each location, five grazing enterprises (self-replacing Merino ewes, crossbred ewes, self-replacing Angus beef cattle, Angus steers and Merino wethers) were modelled. Management policies (livestock replacement, the timing of the reproductive cycle, the sale of young stock and thresholds for supplementary feeding) were not changed between 1899 and 2010. For each set of 15 financial years, annual operating profits were calculated as the gross margin less overhead costs, an operator allowance and a further adjustment for the capital cost of the livestock required, and the optimal sustainable stocking rate was computed. The mean and distribution of pasture production and profit in each period were then compared.

<u>Impacts and adaptation across southern Australia in 2030, 2050 and 2070</u>

As its name suggests, much of the *Southern Livestock Adaptation 2030* program – especially the program of producer engagement – focussed on the relatively near term (i.e. climates projected for the year 2030). However the brief of the program included a requirement to consider climate changes out to the year 2070. The activities in this section were carried out to meet this requirement of the program.

Preliminary studies in New South Wales

The impact of projected climate changes at 2030, 2050 and 2070 on pasture production, sustainable stocking rates, deep drainage and livestock methane emissions was evaluated for representative grazing systems at eight locations across southern New South Wales that had been the subject of producer workshops in the partner project run by NSW Department of Primary Industries.

Grazing systems were analysed using the GrassGro decision support tool. Climate projections at the eight locations from four GCMs under the SRES A2 emissions scenario (a high emissions scenario) were downscaled to daily weather sequences. GrassGro was used to carry out a simulation experiment with the following factors: location (8) x climate (historical + 4 GCMs x 3 future years) x stocking rate (11-16 levels depending on the location). For each simulation, physical and financial outputs (rainfall, temperature, pasture growth rates and composition, conception and weaning rates, wool and livestock sales and amounts of supplementary feeding, and the elements of a gross margin) were recorded, and the optimal sustainable stocking rate estimated given a requirement that ground cover (averaged over the farm) should be less than 0.70 on no more than 7% of days.

Representative grazing systems across southern Australia

The above preliminary study had a limited spatial extent, and only a single grazing enterprise was modelled at each of the eight locations. In order to extend it to a wider area of southern Australia, a representative set of grazing systems was systematically specified for 25 locations.

The set of locations was chosen by dividing the southern part of Australia into regions of approximately equal gross value of agricultural production. A single location was selected (from among those with measured weather data) to represent each region. For each location, a representative set of soils and pastures was then described using the attributes required by the GRAZPLAN simulation models. Wherever possible, the soil and pasture information was drawn from GrassGro "farm systems" developed by State agency officers as part of their modelling work in *Southern Livestock Adaptation 2030*. At locations in the cereal-livestock zone, consumption of stubbles was included in the grazing systems.

A set of 5 livestock enterprises was then modelled at each of the 25 locations:

- self-replacing Merino ewes;
- crossbred ewes purchased annually and producing prime lambs;
- wethers growing fine wool; and
- self-replacing beef cows;
- steer finishing.

Within each enterprise, the same livestock genotypes, prices for livestock and wool and variable costs of production were assumed across all locations in order to facilitate comparisons across sites. Management policies, on the other hand, were described separately for each of the 125 location x enterprise combinations. Management information was drawn from the GrassGro "farm systems" developed by State agency officers wherever possible; otherwise expert opinion, literature accounts and test simulations with GrassGro were used to derive sensible values.

The result of this process was a consistently-defined set of modelled grazing systems that is representative of present-day broadacre grazing systems across southern Australia It complements the wide range of locally-specific farm systems developed in State-based projects by providing a more even coverage of southern Australia and by using consistent animal genotypes and financial information.

Identification of adaptation options

Our literature review located a large list of possible changes to broadacre grazing systems that might be considered as adaptations to climate change, but little or no information that would allow us to identify adaptations that were likely to prove effective over large areas. We therefore prioritized the various possibilities from the results of our preliminary studies and by taking producers' views into account, drawing on the lists of potential adaptations elicited at producer workshops held by partner *Southern Livestock Adaptation 2030* projects.

The resulting set of candidate adaptations to climate change fell into three main classes: changes to the feedbase, changes to livestock genetics and changes to livestock management.

Table 1. Adaptation options that were modelled at 25 locations and for each of the 5 livestock enterprises for which they were meaningful

Feedbase adaptations	Genetic adaptations	Management adaptations
1. Higher soil fertility	4. Increased breed standard reference weight	8. Confinement feeding in summers with low pasture mass
2. Management to remove annual legumes, in order to slow the loss of ground cover	5. Increased wool production at constant standard reference weight	9. Altered stocking rate
3. Sowing a portion of land to lucerne pastures	6. Increased sire standard reference weight	
	7. Increased conception rate	

Some of the genetic adaptations were applicable to only some of the enterprise types. Based on the available literature, linear increases (0.5%/year in the first year) were assumed to be achievable for standard reference weights and the ratio (potential fleece weight:standard reference weight), so that genetic gain was taken to result in different animal genotypes at each future date. Initial achievable increases in conception rate were assumed to be between 0.5 and 0.75%/year depending on the enterprise. Altered stocking rate was a special case, as it was always considered in combination with every other adaptation.

Evaluation of impacts and of adaptation options

A series of large factorial simulation experiments was conducted, in which each of the 5 x 25 GrassGro farm systems was simulated with 30 years of weather from the historical record and from the downscaled weather for each of 4 GCMs at 2030, 2050 and 2070 (i.e. 13 climates). Each combination was modelled at a wide range of stocking rates, and the optimal sustainable stocking rate (as defined above) was identified by interpolating between the simulation results. All 1625 comparisons (location x enterprise x GCM x year) were made at the optimal stocking rates.

The first simulation experiment used unmodified soils, pastures, livestock and management. It was used to evaluate the impact of the projected climates on pasture production, consumption of forage by livestock, the conversion of consumed forage into meat and wool and the income and operating profit.

A second series of simulation experiments was then carried out, in which a single attribute of each modelled grazing system was altered to introduce one of the 8 kinds of adaptation, and the effect on productivity and profit assessed (once adjusted to a new optimal sustainable stocking rate) for each of the adaptations. Multiple levels of some of the adaptations were trialled (increased soil fertility at 2 site-specific levels, introduction of lucerne at 20% and 40% of land area, and confinement feeding at threshold levels for livestock removal of 1000, 1500 and 2000 kg/ha). The “relative effectiveness” of each adaptation was computed as:

$$\text{Relative Effectiveness} = \frac{\text{(Profit with adaptation) - (Profit without adaptation)}}{\text{(Historical Profit) - (Profit without adaptation)}}$$

In the third set of simulation experiments, adaptations were combined in different ways in an attempt to find grazing systems that were well-adapted to future climates. In this work the focus was placed on identifying robust systems, i.e. combinations of adaptations that would return grazing systems to sustainable profitability both across the range of possible futures represented by the GCMs and over the whole of the 2030-2070 period. With 8 distinct adaptation types (plus stocking rate), there were at least 255 different combinations that could have been evaluated; the limited available computing resources meant that only a subset of these possibilities could be examined. Accordingly, the adaptation combinations reported below are not necessarily "optimal" but are rather "best examined" grazing systems.

Capacity building & support for local impacts and adaptation analyses

Developing a network of model users

13 members of the partner *Southern Livestock Adaptation 2030* projects, from organizations in 5 States, were trained in the use of GrassGro version 3 during the life of the project. Approximately 20 GrassGro users were also provided with training in the concepts underlying climate change impacts R&D and the use of GrassGro for climate change analyses. Significant time was devoted to ensuring that once trained, these participants in partner projects could use GrassGro with confidence; activities toward this aim included carrying out validation studies against local experimental data sets (and upgrading GrassGro in response).

Participation in regional climate impacts and adaptation studies

Project team members travelled to SA, WA and Tasmania to assist partner projects with the development of GrassGro "farm systems" that could be used as the basis of regionally-specific climate change impact analyses. We participated directly in 2 WA regional workshops and one in Tasmania.

Extensive support was provided to partner project teams via remote (telephone and internet) channels. Support activities included:

- Interpretation of agronomic or physiological principles underlying key outputs;
- Suggesting ways to modify GrassGro farm systems so that reference simulations were better aligned with expected or measured outcomes;
- Assistance with customization of output reports;
- Interpretation of statistical measures, including those used to derive box-plots, long-term percentiles and other variability metrics; and
- Acting as the *de facto* source of downscaled climate information for the SA, WA and Victorian state-based projects plus some of the NSW participants;

Expanding the applicability of the models – parameter set development

CO_2 responses

The equations in the GRAZPLAN pasture growth model that describe plant responses to increased atmospheric CO_2 were derived in a previous project from an analysis of the published literature. In order to test how well these modifications predict real-world pasture response to CO_2, we used the GRAZPLAN pasture model – including its N response logic – to simulate a cutting experiment in which pasture swards (subterranean clover and phalaris monocultures and their mixture) were grown at Canberra in elevated CO_2, in warmer temperatures and in the combination of the two (Lilley *et al.* 2001).

Native grass pastures

There is a substantial area of central and northern New South Wales where native pastures containing C_4 perennial grasses are an important part of the feedbase. If the GrassGro decision support tool was to be used for climate change impacts and adaptation studies in these regions then this pasture type needed to be available in its underlying pasture growth model. In the NPICC temperate pastures database (Pearson *et al.* 1997), redgrass (*Bothriochloa macra*) is recorded as the most common native C_4 species; we therefore developed a parameter set for the GRAZPLAN pasture growth model that represented this species.

Pasture parameter development proceeded by a combination of literature review together with validation/calibration simulations against datasets from grazing experiments. Two grazing trial data sets were acquired (one at Armidale and one at Barraba, NSW) for the purpose. In order to accurately reflect management activities, all experiments were modelled using the AusFarm software (Moore 2001). Apart from the management rules, the model configurations that were used were compatible with the GrassGro decision support tool, i.e. the water balance model in GrassGro was used and responses of growth to soil fertility were modelled by using a common “fertility scalar” for all pasture species in each plot.

Introduced perennial C_4 grasses

Kikuyu (*Pennisteum clandestinum*) is the most widely used introduced C_4 perennial grass in southern Australia according to Pearson et al. (1997). Development of a parameter set for kikuyu was carried out using similar techniques to the development work for redgrass, using 3 experimental data sets (2 cutting experiments from coastal NSW and a grazing trial at Albany, WA).

<u>Communication and governance</u>

Regional producer workshops were the centrepiece of communication activities in *Southern Livestock Adaptation 2030*. Two other communication channels, which aimed to reach different potential audiences for R&D findings, were also part of the program’s design:

- Short reports that cater to producers who are not motivated to attend a workshop, but are seeking an introduction to climate change adaptation in their region; and
- A workshop designed to communicate program findings to policymakers and other industry stakeholders.

In conjunction with the *Southern Livestock Adaptation 2030* program coordinator and the NSW partner project, we developed a prototype of a software system that delivered context-specific information on climate change adaptation to readers over the Internet. This system consisted of a set of related HTML pages that allowed users to navigate to the region or enterprise in which they were interested; a database server that managed the short reports (including tying them to a specific author, whose photograph was displayed); a facility to attach audio content to short reports, again so as to make the user’s experience more personal; ancillary Web pages for more general information about climate change and its effects on grazing systems; and a draft work flow for preparing the short reports in an efficient fashion. This prototype was used as the basis for a contract that was let by *Southern Livestock Adaptation 2030* to implement a production version of the short reporting system.

As part of a wider *Southern Livestock Adaptation 2030* program team, Andrew Moore played an active role in organizing the policy-oriented workshop, which was held on 18 May 2012 in Canberra and was attended by 30 people. He also made a presentation on “Research findings – broadacre impacts and adaptations” to the workshop.

Andrew Moore also acted as a member of the program steering committee of *Southern Livestock Adaptation 2030*. He attended all meetings of this committee.

Results

<u>Literature review: natural selection in Australian pastures under climate change</u>

Significant levels of genetic variation are known to occur in both native and introduced pasture species in Australia. Variation for a range of climate-relevant traits

Table 2. Relative change in long-term average annual profit after undertaking each of a set of adaptation options under shorter growing seasons, relative to a 1970-1999 historical baseline with no adaptation, at seven locations across southern Australia. Cells shaded in green denote an improvement of 2% or more relative to no adaptation under shorter growing seasons; cells shaded in red denote a decline in profit of 2% or more relative to no adaptation under shorter growing seasons.

Adaptation option	Hamilton	Goulburn	Wagga Wagga	Katanning	Cowra	Lucindale	Mt Barker
Confinement feeding (2000 kg /ha)	green	green	green	red	green		green
Confinement feeding (1500 kg/ha)	green	green	green	red	green	green	green
Confinement feeding (500 kg/ha)				red			
1 Nov mating, first joining at 6 months	green		red	red	red	red	red
1 Nov mating, first joining at 18 months			red	red		red	red
1 Nov mating, first joining at 30 months			red	red	red	red	red
1 Dec mating, first joining at 6 months							green
1 Dec mating, first joining at 30 months	red		red	red	green	red	red
Early annual grass added to the pasture	green				green	red	green
Very early annual grass added to the pasture	green		red	red	green		green
Increased pasture fertility	red	green		red	red	red	

is known to exist in a range of Australian pasture species. These traits are known to be heritable and responsive to selection in some introduced species, but the heritability or potential response to selection of these traits in Australian native pasture species is unknown. The extent of variation for traits associated with drought and heat tolerance is not known, except in a restricted set of introduced species such as *Phalaris aquatica* and *Lolium rigidum*.

Paleobotanical evidence suggests that climate-driven evolution does not, in general, result in the broadening of species' physiological niches; changes in species' distributions should therefore broadly track changes in climate, assuming adequate dispersal. On the other hand, theoretical and contemporary evidence indicates that local adaptation could potentially alleviate some of the adverse effects of climate change, especially in range-core areas where plant population sizes and genetic variation are large.

<u>Adaptations for shorter growing seasons</u>

Confinement feeding was the most generally applicable adaptation option under shorter, more intense growing seasons; starting confinement at a threshold of 1500 kg/ha improved profit at 6 of the 7 locations in the simulation study. Adding early-flowering annual grass to the pasture improved profit by at least 2% of historical levels at 3 of the 7 locations. At the prices assumed, the mating time options were not effective adaptation options for dealing with shorter but more intense growing seasons. Multiple management adaptations were advantageous at locations with relatively longer growing seasons, such as Hamilton, Goulburn and Mount Barker. Adaptation strategies at sites with relatively short duration seasons such as Lucindale and Katanning appear more limited.

Most reductions in profit were a result of the necessity to reduce stocking rates to meet the minimum ground cover constraints. Strategies that allowed the greatest resting of pastures (e.g. confinement feeding with a high herbage mass threshold for confinement) were generally most beneficial, since they allowed recovery of pasture growth and restoration of ground cover. The results of this preliminary study led us to place considerable emphasis on adaptation options that would reduce the frequency of low ground cover in the main adaptation study. More details of this analysis can be found in Appendix 3.

Will managing for climate variability also manage for climate change?

Different realizations of the same GCM showed large differences in decadal average rainfalls. Despite reducing rainfall, total pasture production at Lucindale was predicted to rise at first under both GCMs, with most of the increase in the winter; however the end of the pasture growing season became earlier. Clover contents were also predicted to increase over time. The use of a confinement feeding rule in the management policy allowed stocking rates to be maintained (in most cases) at or above historical-optimum levels, so that long-run average profitability under unchanged management rose gradually until about 2060 and then declined.

Pannell's (2010) contention that on-farm practice change can keep pace with a changing climate was clearly borne out by this case study. The long-term shifts in profitability over time were quite small relative to the year-to-year variability. On average, all four adaptation policies – including no change – produced risk-adjusted profit levels over 2010-99 that were higher than that of the 1990-2010 base period. None of the four adaptation policies consistently outranked all others in terms of risk-adjusted profit. The "forecast" policy was quite robust, improving on no adaptation in 7 of 8 climate+price scenarios, but it usually only provided a modest increase in risk-adjusted average profit. The "incremental" policy did better – often much better – in half the cases but was not resilient to uncertainty in future climate. This study is reported more fully in Appendix 4.

An unexpected finding was that for the "incremental" adaptation policy and the ECHAM5/MPI-OM projected climate, major differences arose between realizations of the same changing climate. It appears that intra-decadal variation around the same mean climate and prices can result in very different trajectories under incremental changes in management.

Medium-term climatic variability and its effects on pasture and livestock production

Taken across southern Australia as a whole, the 14-year period from 1997 to 2010 was drier than any of the 7 preceding periods starting in 1899, and this was reflected in the modelled pasture production; the area-weighted average rainfall and ANPP for the 1997-2010 period were both 10% below the 1899-1996 average. The 1899-1912 and 1927-40 periods also showed lower average annual NPP across southern Australia than the other 5 periods, but at the sub-continental scale it is necessary to look back 70 years to find a sustained period of reduced potential pasture growth such as that experienced recently. However, the spatial average conceals considerable spatial variation: across the South Australian locations, area-weighted average pasture growth was 22% lower in 1997-2010 compared to the 1899-1996 average, while in NSW and Tasmania (Launceston) the corresponding decline was only 4%. For NSW, however, the period of reduced pasture growth in 1997-2010 followed on from the most productive of the eight 14-year periods in 1983-1996.

While there was considerable location-to-location variation, there was a general tendency for the profitability of grazing enterprises to decrease over the 1899-2010 period in Western Australia and to increase and then decrease in Victoria and much of South Australia (Figure 1). In most of New South Wales, the period from 1899-2010 saw steady increases in profitability (at Armidale, this trend continued to 2010); as a result, for the New South Wales locations the profitability of the 1997-2010 period, while much lower than that of the preceding 14 years, was generally inside the range encountered in the historical weather record.

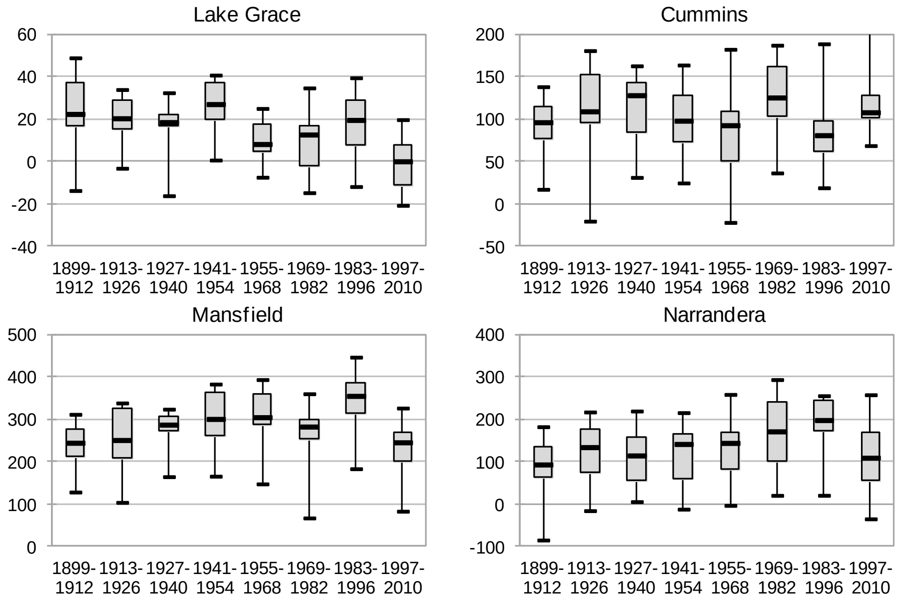


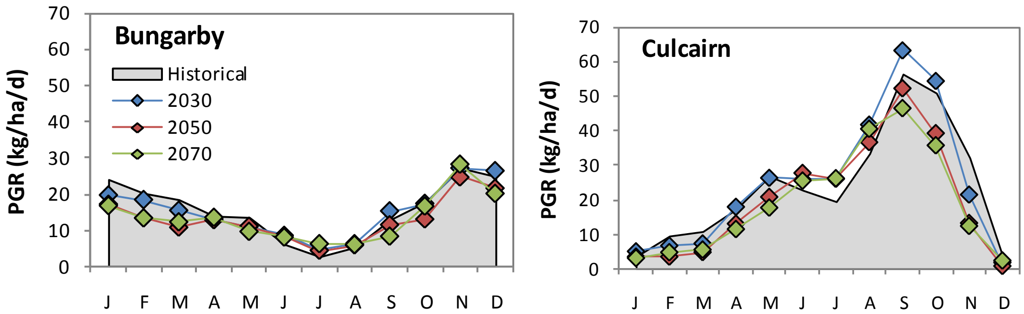
Figure 1. Boxplots showing modelled annual operating profit of a Merino ewe enterprise over 7 periods from 1899 to 2010 at 4 locations across southern Australia. The scales for each location are different so as to show the differences between periods more clearly. The management of each modelled grazing system is identical in each period within each location, except that the optimal sustainable stocking rate for each period has been selected.

There was no evidence that the variability of modelled ANPP or profitability (measured as the standard deviation) had increased, either over the historical record or in the 1997-2010 period in particular.

<u>Impacts of climate change across southern Australia in 2030, 2050 and 2070</u>

The preliminary study for southern NSW is reported more fully in Appendix 6. Projected climate changes were highly consistent across the eight locations (which ranged from Moss Vale in the Southern Highlands to Culcairn in the eastern Riverina). By 2070, three of the four GCMs projected, lower annual rainfall at most of the locations. Projected changes in total rainfall largely determined the changes in pasture growth (aboveground net primary productivity) at all eight locations. At the majority of sites, a given relative change in rainfall was predicted to produce an approximately proportionate change in pasture growth. At Bungarby in the Southern Tablelands, however, each 1% change in annual rainfall induced roughly 1.4% change in pasture growth.

Figure 2. Modelled long-term average monthly pasture growth rates (PGR) at Culcairn, NSW and Bungarby, NSW for climates projected by the UKMO-HADGEM1 model under the SRES A2 emissions scenario. Historical (1970-1999) growth rates for each month are shown as grey shaded areas for comparison. The progressive shortening of the growing season and an increase in winter growth rates can be seen clearly. Corresponding plots for six other locations can be found in Appendix 1.



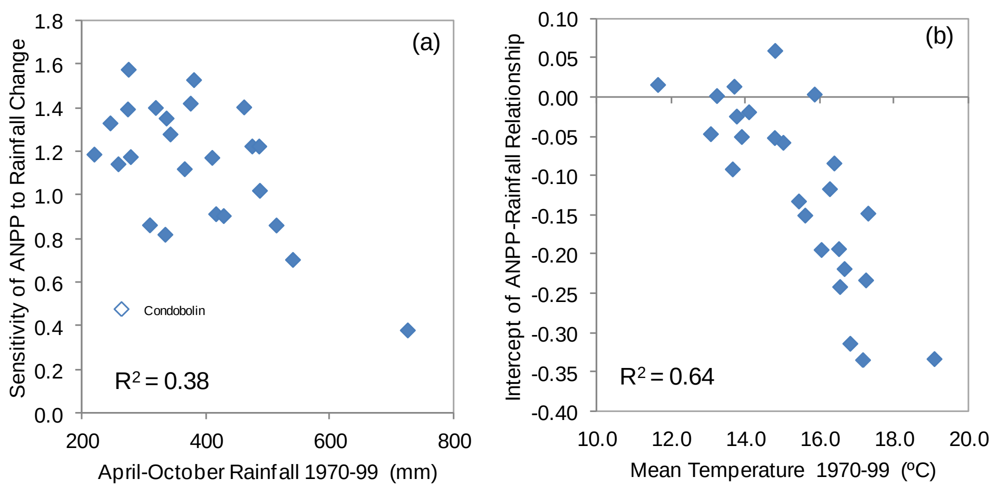
The direction of changes in stocking rate, livestock income and profitability was largely determined by the direction of change in rainfall. Stocking rates declined by a larger relative amount than rainfall; income per DSE remained fairly stable, so that changes in gross income were similar in all cases to changes in stocking rate. Owing to the effect of fixed and overhead costs, profit declined faster in relative terms than income. Levels of deep drainage varied widely from location to location; changes in drainage under altered climates were primarily driven by changes in rainfall. None of the projected climate changes altered the overall quality of pasture consumed enough to shift the expected production of methane per DSE, so that projected changes in livestock methane emissions per hectare were almost entirely driven by the changes in the sustainable optimum stocking rate.

The main climate change impacts analysis (Appendix 7) showed significant differences between the GCMs at each future date. For example, under projections from the CCSM3 model the total (area-weighted) pasture ANPP in the study area was modelled to decrease by 7% in 2050 and 8% in 2070, while for GFDL-CM2.1 total pasture ANPP was estimated to decrease by 20% in 2050 and 34% in 2070. Changes in rainfall were the main determinant of the modelled ANPP changes at most locations, and the sensitivity of ANPP to changes in rainfall was greater in lower-rainfall environments. There was, therefore, a strong tendency for locations with lower annual rainfall to show larger decreases in annual ANPP, particularly in Western Australia (Figure 3).

For the majority of location x projected climate combinations, the optimal sustainable stocking rates were lower than the historical value. In the vast majority of enterprise x location x projected climate combinations – especially in 2050 and 2070 – the proportion of pasture growth that was consumed was lower than in the historical simulation, i.e. utilization rates declined as well as pasture production.

Changes in the climate within each location had relatively little effect on the conversion of consumed pasture into product and hence income. As a result, the

Figure 3. Cross-location comparisons of the overall climate change responses of pasture aboveground net primary productivity. (a) Relationship between the sensitivity of ANPP to change in rainfall and historical mean growing season rainfall. (b) Relationship between the relative change in ANPP when normalized to zero rainfall change and historical mean annual temperature. Normalized ANPP changes are estimated as the intercept from a linear regression over three future dates (2030, 32050 and 2070) and 4 GCMs.



changes in long-term average profit from Merino ewe enterprises (Figure 4) were driven by the amount of pasture that can be consumed without reducing ground cover below threshold levels. By 2050 Merino ewe production in most regions is predicted to produce substantially less income in most regions under at least 3 of the 4 GCM projections; under the climate projected by the most favourable GCM (CCSM3) the average reduction in annual income over all regions was 24% in 2050 and 23% in 2070, while for GFDL-CM2.1 the corresponding reductions in income were 44% and 57%.

When averaged over all GCMs and livestock enterprises, operating profit at the sustainable stocking rate decreased by 38% in 2030, 48% in 2050 and 67% in 2070. These decreases are much greater than the corresponding reductions in pasture ANPP (18%, 21% and 30% respectively). A somewhat unexpected result is the large size of the overall profitability decline by 2030; previous studies (including our preliminary analysis) have concentrated on south-eastern Australia where effects on profit to 2030 are relatively smaller (Figure 4).

At 6 low-rainfall locations (Dalwallinu, Lake Grace, Esperance, Kyancutta, Lameroo and Birchip) stocking rates and hence pasture consumption were reduced to negligible levels in a number of projected climates. For these combinations of location and projected climate, the ground cover constraint cannot be met even at minimal stocking rates, i.e. there is no feasible grazing system with the present-day feedbase.

For the majority of location x projected climate combinations, the optimal sustainable stocking rates were lower than the historical value. As a result, the total quantity of pasture consumed by livestock was generally lower under the projected future climates (total pasture intake was lower in between 82% and 97% of cases, depending on the livestock enterprise). In the vast majority of enterprise x location x projected climate combinations – especially in 2050 and 2070 – the proportion of pasture growth that was consumed was lower than in the historical simulation.

Figure 4. Modelled changes in aboveground net primary productivity of pastures across southern Australia resulting from climate changes projected by 4 GCMs under the SRES A2 scenario. Values shown are changes relative to ANPP in the 1970-1999 base scenario. ANPP values are averaged over the 5 livestock enterprises at their optimal sustainable stocking rates.

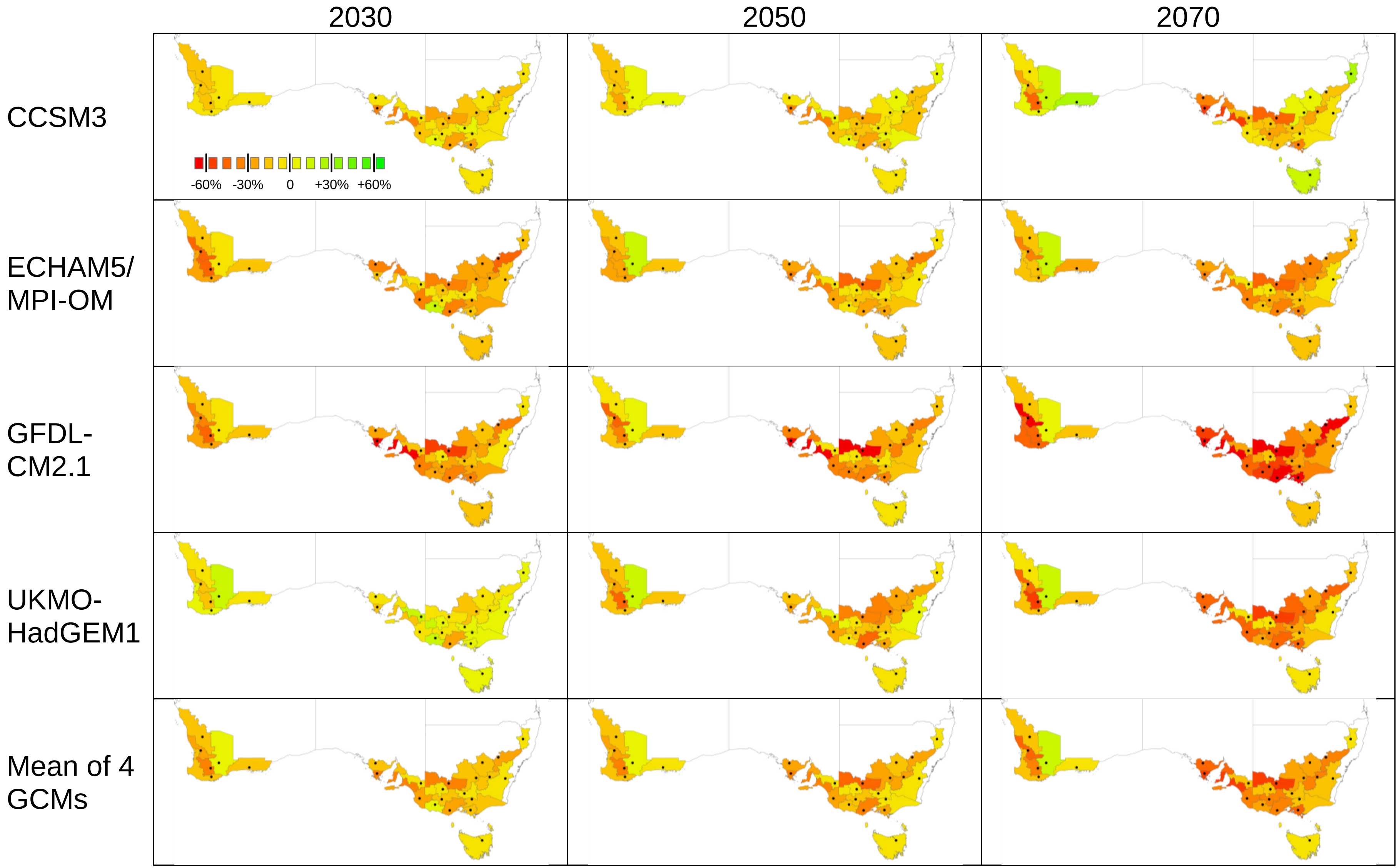


Figure 5. Modelled changes in long-term average operating profit from Merino ewe enterprises modelled across southern Australia resulting from climate changes projected by 4 GCMs under the SRES A2 scenario. Values shown are changes relative to average annual profit modelled for the 1970-1999 base scenario. All profits are computed at the optimal sustainable stocking rate for the relevant scenario. Note that the shading scale is different to that in Figure 4.

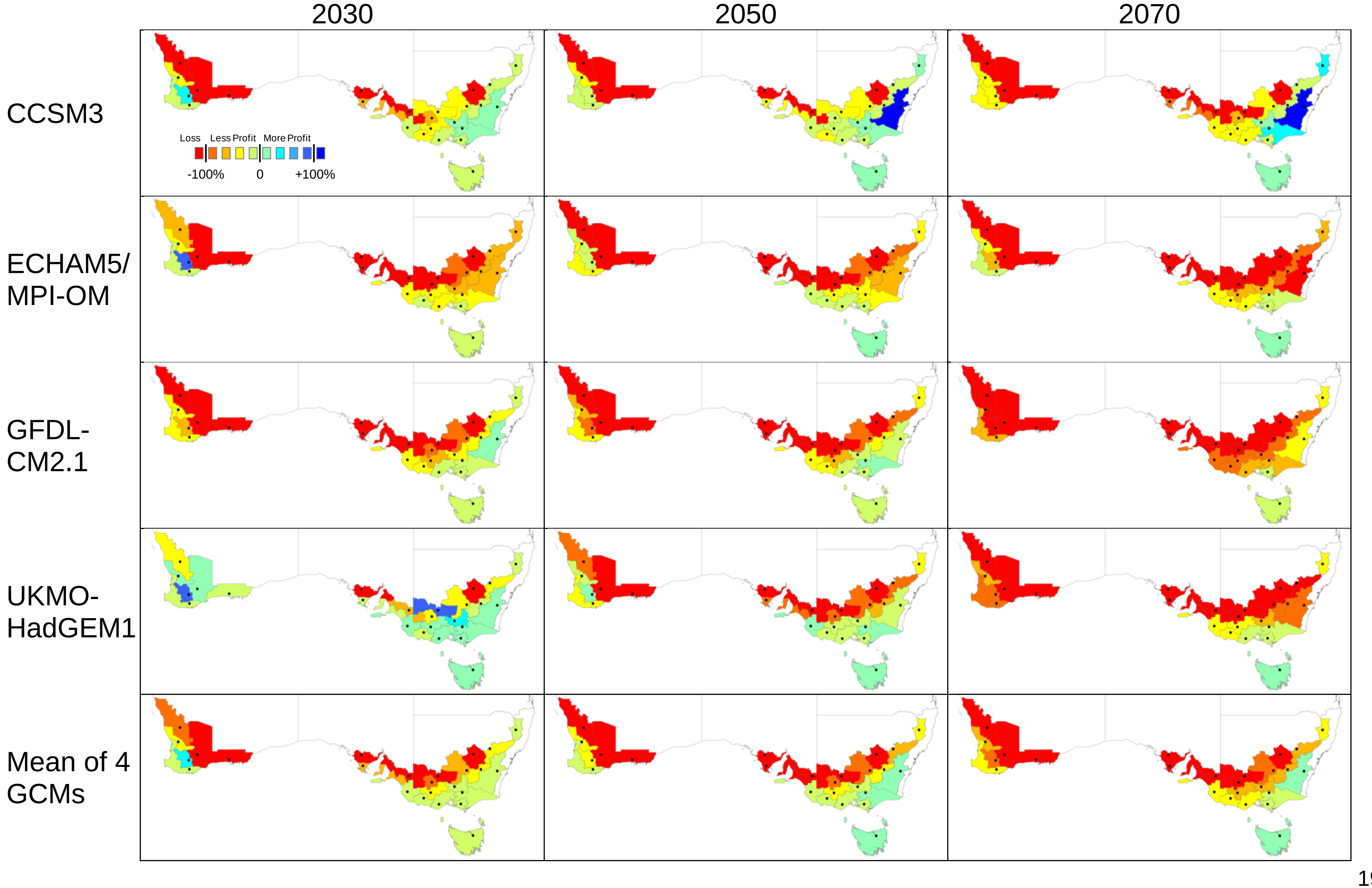


Table 2. Relative effectiveness of a range of different potential adaptations in recovering the impact of climate change on the total value of livestock production across southern Australia (0.0 = no benefit; 1.0 = a return to the 1970-99 baseline value of production). Adaptations were only applied to those location x enterprise combinations where they increased profit at the sustainable optimum stocking rate. Values are averages over 4 GCMs.

	2030	2050	2070
Higher soil fertility	0.62	0.67	0.44
Sowing a portion of land to lucerne pastures	0.45	0.50	0.41
Increased conception rate	0.15	0.32	0.31
Increased breed standard reference weight	0.11	0.27	0.28
Confinement feeding in summers with low pasture mass	0.22	0.26	0.18
Increased sire standard reference weight	0.07	0.16	0.16
Increased wool production at constant standard reference weight	0.03	0.06	0.05
Management to remove annual legumes	0.01	0.01	0.01

Adaptations to climate change across southern Australia in 2030, 2050 and 2070

Relative effectiveness of individual adaptations

Increasing soil fertility was the most generally applicable adaptation option (Table 2); under the financial assumptions that were used, it was cost-effective for nearly all location x enterprise combinations. When averaged over all locations and GCMs, this adaptation option recovered up to two-thirds of the profitability losses due to climate change.

The next most effective adaptation option overall was sowing a portion of the land area to lucerne pastures. This option differed from higher soil fertility, however, in that it was effective at some locations (the high- and medium-rainfall parts of Western Australia and Goulburn) and not at others (for example Launceston). Similarly, confinement feeding was effective only at particular locations such as Colac and Mount Barker. The best genetic option to pursue differed from location to location and enterprise to enterprise. Because the genetic improvement adaptations were assumed to result in continual improvements over time, they maintained their effectiveness in 2070 to a greater extent than modifications to the feedbase or to livestock management.

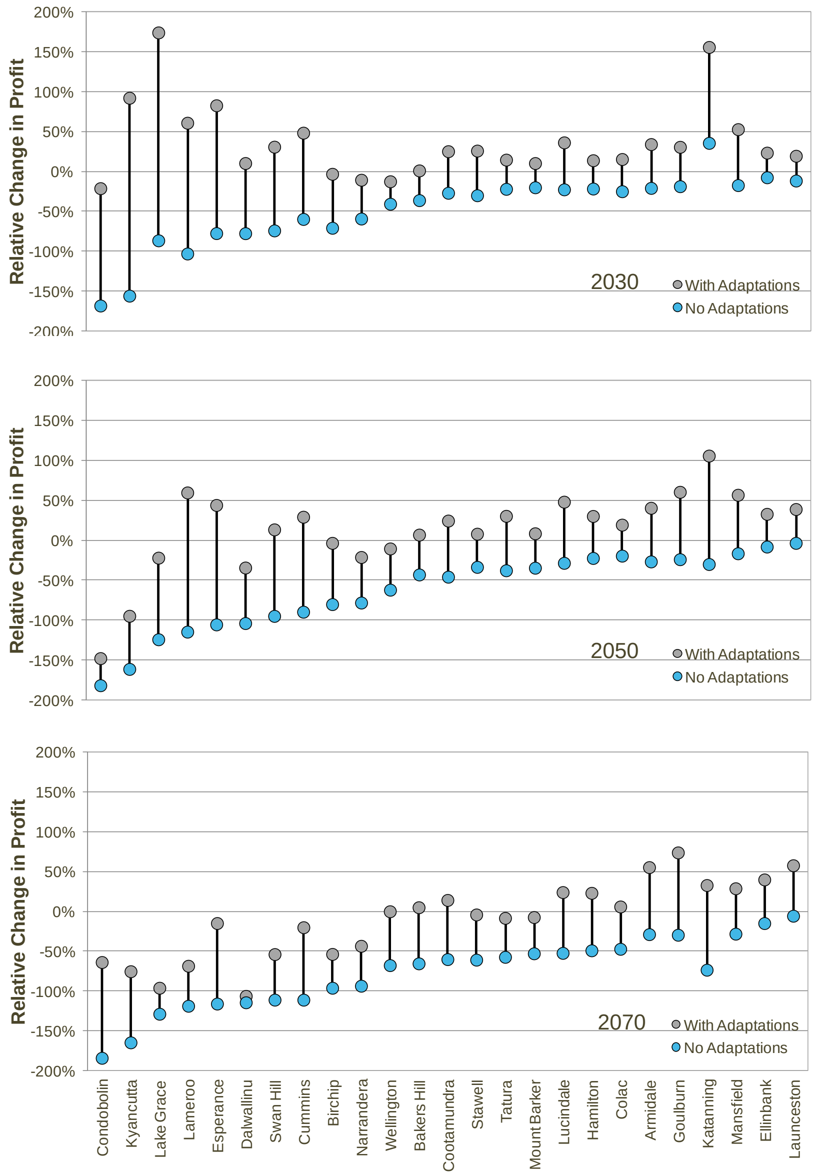
The single most important point to emerge from Table 2, however, is that no single adaptation strategy can be expected to be fully effective in returning all future southern Australian livestock production systems to historical levels of productivity.

Combinations of adaptations

The results of simulations implementing combinations of adaptations for the Merino ewe enterprise are compared with simulations with no adaptations in Figure 5. The actual combinations of adaptations represented in Figure 5 are very different from location to location. At 2030, the best combination of adaptations that we have been able to identify is sufficient in nearly all cases to return these grazing systems to their 1970-99 levels of profitability; there is a tendency for the locations at which climate change impact is greatest to show the greater effectiveness of the adaptations that have been examined.

This picture changes at 2050 and 2070. At these dates the magnitude of climate change impacts on profitability generally becomes greater, and the degree of recovery of profitability from adaptation at the highly-impacted locations (mostly at the dry margin of the cereal-livestock zone) becomes smaller, so that major reductions in profitability remain even after adaptation of the grazing systems.

Figure 5. Change in profitability of Merino ewe enterprises at 25 locations across southern Australia under projected future climates before (blue circles) and after (grey circles) the introduction of the best-available, locally-specific combination of adaptation options. Profitability values are averages over 4 GCMs and are given as changes relative to profit 1970-99 climate, so that 0% denotes historical levels of profitability and values below -100% denote4 systems that operate at a long-term average loss. Locations have been arranged in decreasing order of climate change impact on profitability (averaged over 203, 2050 and 2070).



At the same time the relative amount of technical adaptive capacity at less-impacted locations increases somewhat; as a result, at locations such as Katanning, Goulburn or Mansfield there is a margin of capacity available to cope with other possible future shocks such as a decline in the terms of trade or a disease outbreak.

It should be emphasised, however, that the combinations of adaptations shown in Figure 5 together imply major shifts in the management of livestock farms: a general increase in the intensity of inputs of fertilizer, widespread and long-term adoption of systematic livestock genetic improvement, and a significant increase in the proportion of perennial pastures in the landscape. The potential implementation difficulties associated with each of these changes are significant. For example, increasing soil fertility in mixed farming areas may require a shift in overall land use toward pastures in order to maintain or increase soil organic matter levels, and the widespread adoption of lucerne may be limited by soil constraints.

Nonetheless, our simulation results suggest that some of these adaptations we ahve examined – especially locally-specific genetic improvements and management for increased soil fertility – are likely to be widely cost-effective under current climate, i.e. they are “no-regret” adaptation options that can be advocated immediately.

Expanding the applicability of the GRAZPLAN models

CO_2 responses

Lilley *et al.* (2001) measured enhanced herbage production in the clover under elevated [CO_2], and reduced growth at warm temperature, while there were no treatment effects on herbage biomass in phalaris. The results of the simulations with GRAZPLAN were broadly consistent with these results. The model predicted growth of clover monocultures well for ambient and elevated CO_2 at field temperature (Figure 7), so supporting the CO_2 response functions in the GRAZPLAN model. However, the model over-predicted clover growth at higher temperatures. In the experiment, was no effect of CO_2 or warming on growth of phalaris in monoculture; the GRAZPLAN simulations produced the same result, predicting that the experimental plots were nitrogen-limited.

In contrast to the monoculture, herbage production of phalaris in mixture was enhanced by both elevated [CO_2] and temperature. Responses in the GRAZPLAN simulations were similar in trend but smaller in magnitude than the observed data. Overall, the results of this test of the CO_2 response functions are promising; testing against further data sets is needed, however.

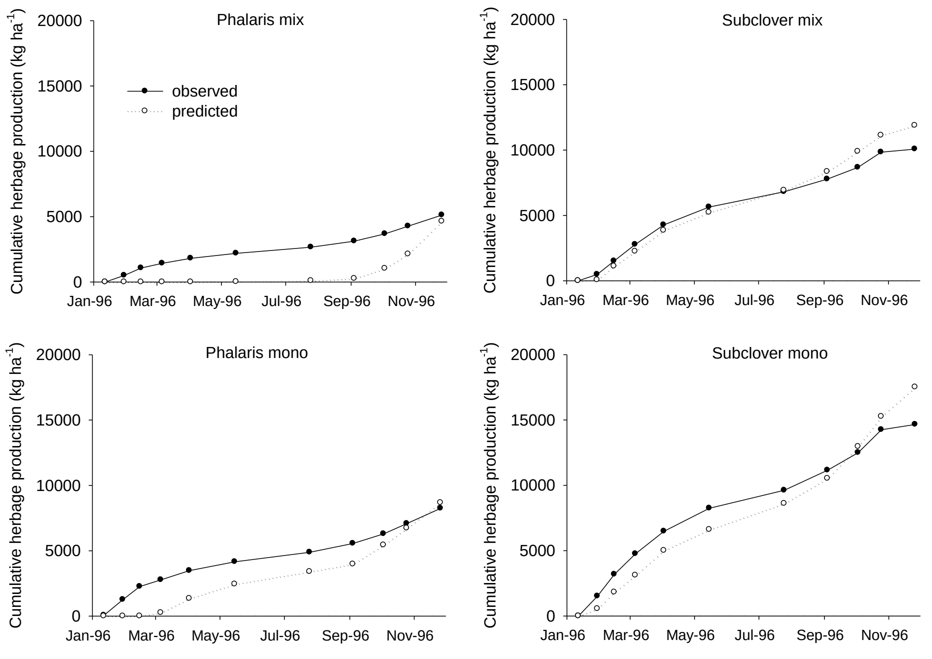
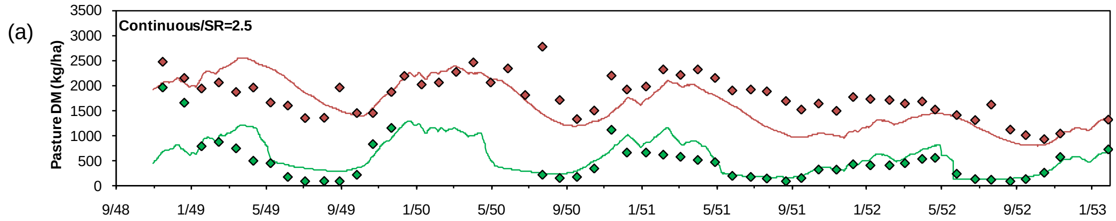


Figure 7. Observed cumulative herbage biomass (greater than 7 cm height) over time measured by Lilley *et al.* (2001) and predicted with GRAZPLAN between December 1995 and November 1996 in the elevated [CO_2] warm temperature treatment.

Figure 8. Simulation of an unfertilized redgrass-dominant pasture at Armidale, NSW stocked at 2.5 dry sheep/ha between October 1948 and October 1952. (a) Actual (symbols) and modelled (lines) green and total herbage mass, (b) actual (LHS) and modelled (RHS) botanical composition by weight at 12 measurement dates Note that the data set does not distinguish between grass species, so that the grey bars the proportion of grass (i.e. redgrass+*Austrodanthonia*).



Native grass pastures

The dynamics of herbage mass in the Armidale grazing experiment were quite successfully modelled (green mass: RMSD = 204 kg/ha; total mass: RMSD = 398 kg/ha), with the characteristic high ratio of dead to green *Bothriochloa* being successfully captured (Figure 8). The simulation of botanical composition was pleasing: the modelled pasture retained all four functional groups and the annuals correctly appeared as only small components of the pasture. There was, however, a systematic pattern of under-prediction of sheep weight change in spring each year.
Results of the validation simulations for the Barraba experiment were not as good as for the Armidale experiment; the general patterns of herbage availability were reproduced but the RMSD for pasture mass was 1066 kg/ha. The relationship between measured and modelled pasture masses did not depart significantly from the 1:1 line, however. Discrepancies in live weight change predictions showed similar month-to-month variation to the Armidale experiment.

The redgrass parameter set remains a work-in-progress. However it received a good level of acceptance from NSW Department of Primary Industries staff at a GrassGro training workshop in June 2011, and so a decision was taken to release it for use in *Southern Livestock Adaptation 2030*. It has since been used in NSW regional workshops and in the work presented in Appendices 7 and 8.

Introduced perennial C_4 grasses

Development of a kikuyu parameter set proceeded to a point where it be used to successfully simulate growth rates of cut kikuyu swards on the Central Coast of NSW, but performance of the new parameter set in mixtures at Albany was unsatisfactory. This parameter set was therefore not used in the main impacts and adaptation studies. Work to further improve the kikuyu parameter set will continue.

Discussion and Conclusions

Overall, this project has met its objectives and it has played a vital role in the undoubted success of the *Southern Livestock Adaptation 2030* RD&E program.

Knowledge to underpin ongoing engagement about climate change adaptation

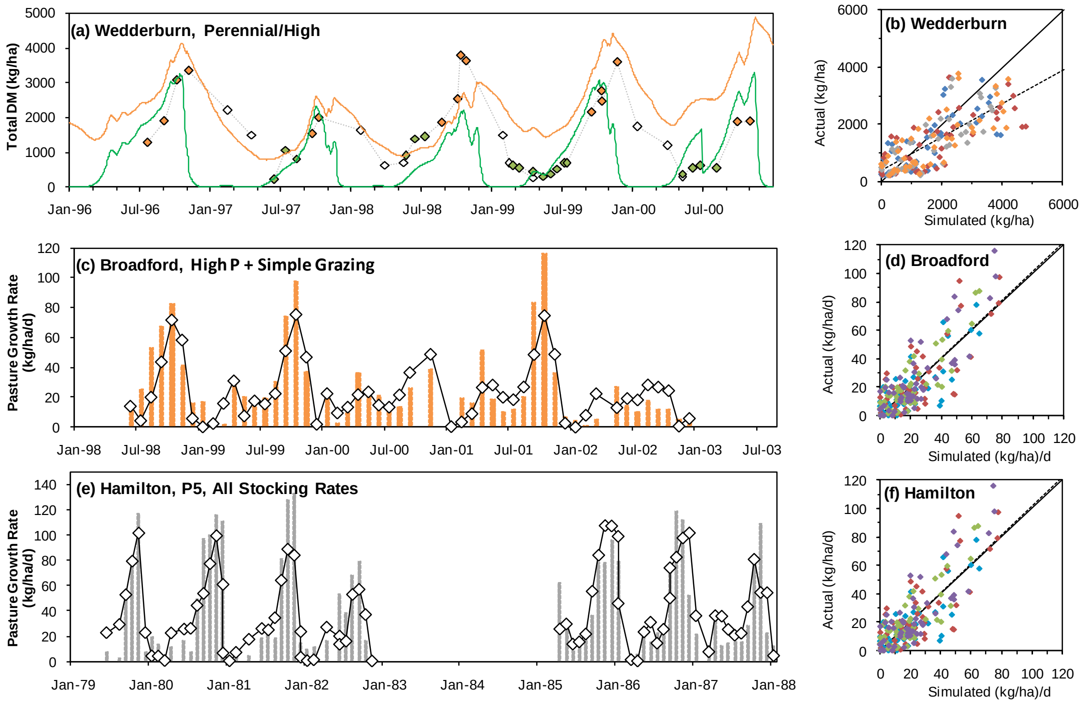
This project has carried out the first systematic analysis of the likely magnitude and rate of climate change impacts on the economic productivity of the southern Australian livestock industries. This work is ground-breaking: no other agricultural climate change study has simultaneously addressed the dimensions of geography, industry segment, time, natural resource management constraints and climate projection uncertainty while considering multiple adaptation strategies singly and in combination.

Despite the enormous complexity of our research question, a set of key messages emerges from the mass of modelling results:

- In the absence of adaptation, the magnitude of climate change impacts will be large; the potential exists for a significant decrease in the total value of livestock production.
- Based on the available projections, there is a real prospect of substantial impacts on pasture growth and its variability in the next twenty years.
- Declines in production and profitability can be expected to be significantly larger than declines in total pasture growth (which has been the focus of most previous research). This differential is caused by the need to leave herbage unconsumed to protect the soil resource, and is probably exacerbated by increased variability in future climates.
- Climate change impacts, and hence the need for adaptive responses, are greatest in the lower-rainfall parts of the cereal-livestock zone and tend to be less severe in the south-eastern parts of the high-rainfall zone.
- Taken across southern Australia, all broadacre livestock enterprises are likely to be affected strongly by projected future climates. It appears that impacts on beef breeding will be somewhat smaller in relative terms than the impacts on other enterprise types; these differences are unlikely to be large enough to make beef cattle more economically attractive than other enterprises, however.
- The uncertainty associated with these projected changes in livestock production is large – and is caused by uncertainty in rainfall projections – but the above trends are discernable nonetheless.
- A range of different adaptations, based on currently-available technologies, are potentially effective in ameliorating the impacts of projected climate changes. The most important of these are:
  - increasing soil fertility, so increasing the water use efficiency of pasture growth;
  - ongoing genetic improvement of livestock;
  - introduction or increased use of summer-active perennials (particularly lucerne);
  - in some locations, the use of confinement feeding to protect ground cover.
- No single adaptation will be completely effective adapting the broadacre livestock industries to climate change. In most situations, a combination of adaptive responses will be required.
- It is likely that in 2030, combinations of adaptations can be found to return most livestock production systems to profitability. By 2050 and 2070, on the other hand, our findings suggest that the lower-rainfall parts of the cereal-livestock zone will require either new technologies, a complete re-thinking of the feedbase or else sustained price increases in order for livestock production to remain viable.

Publication of these results in the scientific literature has been slower than intended. Owing to difficulties with recruitment and retention of staff (the latter a symptom of the demand for agricultural scientists with systems analysis skills), the postdoctoral fellowship in this project was filled for only 19 months of a planned 3 years. Dr Jenny Carter was brought into the project team to work on the CO_2 response studies & Mr Scott McDonald to provide technical assistance with the main impacts and adaptation study, but this response did not fully compensate for the gap in the postdoctoral fellowship. The main aspect of the project which suffered from the resulting under-

Figure 9. Selected results of validation simulations at three Victorian locations with the modified pasture parameter sets developed during the project (a, c, e) Time courses of pasture mass (Wedderburn) or pasture growth rate (Broadford and Hamilton) compared against measured data for one of the experimental treatments at each site. (b, d, f) Comparison of actual vs modelled pasture mass or growth rate across all modelled treatments in each experiment.



staffing was the publication of our findings. Publication will be pursued actively during the remainder of the project's life (to 30 June 2012) and beyond.

<u>Awareness of program results by livestock producers</u>

At the beginning of the project, provision was made for the CSIRO project team to participate actively in regional producer workshops, in order to provide readily-accessible scientific backup (and, to some extent, to lend credibility) to the workshop leaders. In the event, our interactions with the state-based project teams took a different form, in which we mostly provided "back office" support to the achievement of the producer awareness goals. The SA, WA, Tasmanian and Victorian project teams were predominantly composed of officers who were inexperienced GrassGro users. With each of these projects we undertook an initial period of training in the "art" of modelling, and of assistance in specifying "farm systems" for use in regional impacts and adaptation work. Once we had helped our state-based colleagues to develop confidence in the performance of GrassGro, however, they found that they did not need our backup when interacting with producers. As a result, the producer workshops that we did attend (especially in Tasmania and WA) were early in each state-based project's work program. The NSW project team was largely self-sustaining, and our interactions with them were of a more advisory nature (through participation in NSW project team meetings) or focussed on more narrowly technical issues such as the development of native grass parameter sets.

The process of establishing confidence in GrassGro was not without its challenges, and it is fair to say that we spent more effort in this area than originally envisaged. The most significant confidence issue we encountered - concern about GrassGro's predictions of patterns of pasture growth in Victoria – was well-founded, however.

The interaction resulted in revisions to the standard pasture model parameter sets that were both necessary and useful (Figure 7). This issue and its resolution provide an excellent example of the way in which the practical application of simulation models can lead to the improvement of their scientific rigour.

The provision of short, context-relevant reports via the Internet is a relatively new approach to producer communication. Our design work on the technical aspects of providing short reports via the Internet was successful in that it gave the program coordinator Steering Committee confidence in the feasibility of this communication channel and an appreciation of the features that a system for report provision would need. Implementation of the system of short reports was taken up as a program-level, rather than a project-level, responsibility.

The stakeholder conference was successful in its aim of engaging a policy and industry audience with the results of *Southern Livestock Adaptation 2030*, and of this project in particular.

<u>Definition of a program for on-farm trialling of key recommendations</u>

One of the objectives of *Southern Livestock Adaptation 2030* was to define a program of on-farm trialling of key recommendations within each of the agro-climatic regions of southern Australia for implementation after 2012. Responsibility for this objective was shared across the projects in the *Southern Livestock Adaptation 2030* program. It was overtaken by events in the final year of the program, in particular the introduction of the Australian Government's Carbon Farming Initiative (CFI). As a result of the CFI and its associated R&D calls, the focus of planning for new work following on from *Southern Livestock Adaptation 2030* shifted toward mitigation of climate change rather than adaptation to it. We played an active role in planning for the livestock sector's response to the CFI, through participation in two workshops organized by MLA; the preparation of a position paper on "adaptation of wool production systems" (the brief actually covered climate variability, climate change adaptation & mitigation) for a research forum held November 2011 as part of implementing the Primary Industries Standing Committee's Wool RD&E Strategy; and the submission of proposals to the *Filling the Research Gap* component of the CFI.

<u>Development of an improved modelling capacity across a range of industry RD&E providers</u>

A "modelling capacity" must be built up from scientific understanding expressed in mathematical models, the implementation of that understanding in usable software and the development of skilled people who can apply the models and software to RD&E activities.

The most important improvement to the scientific capacity of the GRAZPLAN models has been the improvements to the pasture parameter sets that underpin them. In particular, the addition of a C_4 native perennial grass parameter set removes a long-standing constraint to the use of these models in northern NSW.

While a few improvements were made to the GrassGro decision support tool in the course of the project (particularly the reporting of ground cover), the GRAZPLAN software proved to be largely adequate to the tasks required of it both in this project and in the *Southern Livestock Adaptation 2030* program more generally.

As a result, the most important "software" output from this project is the set of consistently-defined, representative models of grazing systems (GrassGro "farm systems"). The set of farm systems developed in this project complement those prepared for regionally-specific studies in our partner projects; they abstract away from local reality to some extent, but this makes them more comparable across locations and livestock sectors. As well as providing a useful starting point for future users of GrassGro, this set of farm systems has potential to be useful in taking geographic variation into account when analysing a wide range of different questions relating to livestock production.

The most significant steps toward a capacity to model southern Australian livestock systems, however, have been in the development of a network of skilled people. Not only have three post-doctoral scientists (2 CSIRO, one University of Melbourne) started to use the GRAZPLAN models in their research, but a network of development officers and extension staff across 5 states has learned to apply these models to practical questions. Importantly, the process of engagement between the CSIRO project team and this state-based network has enabled the latter to develop confidence in the GRAZPLAN models sufficient that they wish to continue using them (as indicated by a successful proposal to the DAFF *Action on the Ground* program by our South Australian partner). As with the set of representative grazing systems, this network of people represents an opportunity to address a range of different issues in a consistent way across Australia, as envisaged by the new PISC industry RD&E strategies.

Where to from here?

The most immediate next step for our project will be to further communicate project findings, and in particular to publish in the peer-reviewed scientific literature. This will be a focus of work in the period until the formal closure of the project in June 2012. We also plan to propose our work as for presentation to the 2012 International Grassland Congress to be held in Sydney.

A second priority needing consideration is how to maintain the momentum developed in the *Southern Livestock Adaptation 2030* program in developing a network of people who can carry out relevant systems analyses for the livestock industries. At the research end of the spectrum, the new DAFF *Filling the Research Gap* program will draw on the expertise developed in this project, but an opportunity needs to be sought to put the skills of the wider group of State-based staff to good use. This should be a priority in project development for the next round of *Filling the Research Gap* and *Action on the Ground* funding proposals.

Our project was part of a highly successful integration of researcher, industry extension and producer expertise, and it was also successful in forming and maintaining links across the boundaries of 5 states. We did not, however complete the integration trifecta by establishing strong working links with companion programs in the Climate Change Research Program addressing other agricultural industries – especially the northern livestock and cropping programs. An important task, therefore, will be to compare and contrast our findings with those from these companion programs, so as to more fully understand the potential consequences of climate change for patterns of land use across our continent. In this way we would contribute to a national assessment of climate change impacts on, and the benefits of effective adaptation for, Australia's primary industries.

Scientific Papers

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Crimp SJ, Stokes CJ, Howden SM, Moore AD, Jacobs B, Brown PR, Ash AJ, Kokic P, Leith P (2010) Managing Murray–Darling Basin livestock systems in a variable and changing climate: challenges and opportunities. *The Rangeland Journal*, **32**, 293-304

Ghahramani A, Moore AD (2012) Feeding management rules as adaptation strategy for natural resources and livestock systems in Southern Australia. In: NCCARF National Adaptation Conference, Melbourne, 26-28 June 2012.

Ghahramani A, Moore AD (submitted) Increasing soil fertility and altering legume-grass balance as adaptation strategies for sustainable livestock production under climate change. To 16th Australian Agronomy Conference.

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List of Appendices

The Appendices to this Final Report present the scientific results of project MBP.0073 in greater detail. They are provided as a separate document.

1. A review of prior work relating to adaptation of southern Australian livestock production to climate change
2. Natural selection in southern Australian pastures under climate change: a brief review
3. Effectiveness of a range of grazing system adaptations in ameliorating the impacts of shorter growing seasons
4. Will managing for climate variability also manage for climate change? A southern Australian grazing system as an example
5. Medium-term climatic variability and its effects on pasture and livestock production: consequences for projections of climate change impacts
6. Impacts of climate change to 2070 at eight locations across southern New South Wales: a preliminary analysis
7. Impacts of climate change across southern Australia in 2030, 2050 and 2070
8. Adaptations to climate change across southern Australia in 2030, 2050 and 2070
9. Testing the responses of the GRAZPLAN model to increased atmospheric CO_2

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Appendix 1. A review of prior work relating to adaptation of southern Australian livestock production to climate change

This short review is intended as a summary of investigations into the impacts of climate change on, and adaptation to climate change by the southern Australian livestock industries prior to the commencement of the Climate Change in Southern Australian Livestock Industries project in September 2009. The focus of this document will be on paddock- and farm-scale changes; the physiological aspects of plant and animal responses to likely climate changes have been reviewed elsewhere (e.g. Ainsworth & Long 2005, Soussana & Lüscher 2007, Marai *et al.* 2007, Moore *et al.* 2008).

<u>Review and overview articles</u>

There are a number of review articles addressing climate change impacts on the Australian livestock industries (Harle *et al.* 2007, Howden *et al.* 2008, Stokes *et al.* 2010, Miller *et al.* 2010). These papers are all high-level summaries that cover entire industries: they therefore contain little quantitative information about climate change impacts. As Stokes *et al.* (2010) put it, "a rigorous analysis of the regional variation in impacts of climate change on grazing lands still needs to be conducted".

These four reviews focus on livestock production in the pastoral zone, with a secondary focus on dairy production (mainly in the chapter by Miller *et al.* 2010). Much less attention is paid to meat and wool production in the high-rainfall and cereal-livestock zones. For example in the book chapter by Stokes *et al.* (2010) on broadacre grazing, over half the text is devoted to issues of specific relevance to rangelands even though only ~15% of the economic value of broadacre livestock production comes from the pastoral zone. This imbalance seems to reflect the history of research investment into studying climate change impacts and also the relative land area.

Pasture growth. The view of changes to pasture growth rates put forward in these reviews – at least to 2030 – is that impacts on broadacre pasture supply will be "noticeable, although not dramatic" (Harle *et al.* 2007) and will be mainly driven by rainfall changes, which are in turn uncertain given the current state of knowledge. As Miller *et al.* (2010) point out, if climate projections of reduced rainfall in southern Australia come to pass then availability of irrigation water will reduce.

Livestock production. All four reviews place greatest emphasis on the likelihood of increasing heat stress on beef cattle (as studied by Howden *et al.* 1999) and on increasing water requirements for stock (Howden & Turnpenny 1997). Both these issues are of especial relevance in the rangelands. Livestock water infrastructure in southern Australia is almost certain to meet any increased demand (supply of livestock water from dams is much more likely to act as a constraint). While the incidence of days of high temperature-humidity index will clearly increase in southern Australia, both cattle and sheep can adapt their behaviour – especially their times of grazing – and so reduce the effect of higher temperatures on their energy balance. The overall importance of heat stress in future southern Australian climates once behavioural adaptations and the annual cycle of energy supply are taken into account, and the relative importance of heat stress to cattle and sheep, are questions needing further examination.

Natural resource management. The main NRM issue raised in these reviews is the risk of increased soil erosion, based on projections of increased rainfall intensity and the possibility of more variable annual rainfall producing more frequent episodes of

Table A1.1. High-priority adaptation options for producer action proposed by Stokes *et al.* (2010) for the broadacre livestock industries and by Miller *et al.* (2010) for dairy production. A priority ranking of 1 is higher. In some cases similar actions on the two lists have been combined; a small number of non-specific statements have been omitted.

Climate change adaptation option	Priority ranking for:	
	Broadacre	Dairy
Use seasonal climate forecasting in decision-making	1	1
Provide extra shade	2	1
Select animal lines that are resilient to higher temperatures	2	2
Improved on-property water use efficiency of irrigation		1
Select drought-tolerant pasture cultivars		1
Fodder conservation and conserved fodder use strategies		1
Forward contracting supply of supplementary feedstock		1
Agist stock during unsuitable conditions		1
Progressive recalculation of safe stocking rates	1	
Improve on-property water management	2	
Greater use of strategic spelling	2	
Improve nutrient management using sown legumes and P fertilizer where appropriate	2	
Modify timing of mating, weaning and supplementation based on seasonal conditions	2	

low ground cover. This question is already receiving considerable attention in CCASALI.

Industry-level issues. Harle *et al.* (2007) devote attention to the possibility that industry production of wool under changing climate and technology will be driven by land use changes driven by differential changes in productivity of wool relative to other agricultural enterprises (cropping, beef and lamb production) even more than the changes in productivity within wool enterprises themselves. Heyhoe *et al.* (2007) assumed for the purposes of an economic analysis that wheat productivity would be more sensitive to rainfall changes than wool and beef productivity, although they did not report the basis of this assumption.

Adaptation options. Each of the four review articles provides a list of possible adaptation options. The book chapters by Stokes *et al.* (2010) and Miller *et al.* (2010) are the first to attempt to prioritize the wide range of adaptations that are possible for the broadacre and intensive livestock industries respectively (Table A1.1). The highest-priority common item is the idea of using seasonal climate forecasting (adapted to take climate trends into account) as a way of managing for climate change incrementally. The other common items relate to avoiding or tolerating the projected increases in heat stress. It is noticeable that the dairy priorities place more emphasis on managing the supply of feed than do the broadacre priorities; this most likely reflects the greater level of inputs into dairy production.

Experimental studies

Small-scale experiments. Roger Gifford & co-workers have carried out a series of experimental studies into the responses of temperate pastures to increased CO_2 and/or temperature in microcosms (Lutze & Gifford 1998a, 1998b, 2000) or temperature gradient tunnels (Lilley *et al.* 2001a, 2001b, Volder *et al.* 2004). These experiments involved very high atmospheric CO_2 treatments of 690-750 ppm and (in the tunnels) temperature increases of 3-4°C, and were carried out under conditions of continuously high water availability. Under these conditions the enhancement of total shoot growth by CO_2 alone was species-specific, ranging from 0-11% for phalaris (*Phalaris aquatica*) monocultures, 14-29% for *Danthonia racemosa* monocultures and 19% for subterranean clover (*Trifolium subterraneum*) monocultures. In a phalaris/clover mixture, however, biomass production of clover increased by 31% and that of phalaris by 40% in the mixture (Lilley *et al.* 2001a). Volder *et al.* (2004) found strongly seasonal responses to increased temperature and CO_2 in phalaris. These responses were generally reduced by warming; a 3.4° temperature increase reduced clover biomass production in monoculture by 28% at ambient CO_2 and by 9% at elevated CO_2, despite the low winter temperatures at the experimental location (Canberra).

The fact that these experiments were all continuously irrigated will have tended to reduce the relative response of biomass production to CO_2, as the "water-sparing" effects of stomatal closure at high CO_2 (e.g. Ferretti *et al.* 2003) would have had no scope to allow later onset of water stress. Lutze & Gifford (1998b) found clear evidence of this effect in their study.

The differing responses of phalaris growth to increased CO_2 in monoculture and in mixture in the experiment of Lilley *et al.* (2001a) suggest the existence of a nitrogen supply interaction. Lutze *et al*. (1998b), however, did not find a trend in the CO_2 fertilization effect across three sharply different levels of N supply to *D. racemosa* microcosms.

Free-air CO_2 enrichment (FACE) experiments. Two FACE experiments have been conducted in environments of direct relevance to southern Australia. Newton *et al.* (2006) report a FACE study on a diverse pasture (containing C_3 and C_4 grasses, legumes and forbs) in New Zealand, while Hovenden *et al.* (2008a, 2008b, 2008c) are carrying out a FACE experiment on a *Themeda triandra*-dominant but botanically diverse native pasture in Tasmania.

Newton *et al.* (2006) found no statistically significant difference in long-term pasture yield between FACE rings grown at ambient CO_2 and 475 ppm, but the measured difference (about 8%) is consistent with the experimental studies described above once the smaller size of the CO_2 treatment (475ppm) is taken into account. They did find an increase in photosynthetic rates under increased CO_2, but there was also an increase of allocation of carbon belowground. N content of individual species declined, but this was offset by an increase in the proportion of legumes in the pastures under increased CO_2. Newton *et al.* (2006) also found evidence that N and P became progressively less available over time under increased CO_2 in this long-term experiment – this phenomenon, termed "progressive nutrient depletion", has been observed by other workers (Luo *et al.* 2004).

Hovenden *et al.* (2008a) reported no increase in biomass production when a CO_2 concentration of 550 ppm and a 2.1°C warming were imposed on a native pasture. Little response to CO_2 would be expected in a plant community that is dominated by a C_4 grass with limited water stress but the lack of a temperature response is somewhat surprising. The site does appear to be nutrient-poor, however. They found some evidence for progressive nutrient depletion under enhanced CO_2, but the measured decreases in inorganic N availability were reversed when warming was also applied. Hovenden *et al.* (2008b) found marked changes in phenology, especially flowering date, in response to temperature increases (but not CO_2 increases), thereby confirming one of the main expected responses of pastures to increased temperature.

The interactions between CO_2, water and nutrient supply in pastures are clearly complex and need further teasing out. In particular, the likelihood of progressive nutrient limitation becoming a major factor in field situations under simultaneous CO_2, temperature and soil moisture changes needs to be evaluated.

Modelling studies

There have been three simulation modelling studies that bear on the issues being addressed by the CCASALI program: a continent-wide study of impacts on native pasture growth by McKeon *et al.* (2009), a multi-site study of impacts on improved pasture growth by Cullen *et al.* (2008, 2009) and a study of impacts and adaptation for pasture and livestock production in the Southern Tablelands of NSW (Moore *et al.* 2009). These three studies have used different simulation models, different time horizons and different approaches to the projection of future climates.

McKeon *et al.* (2009), building on an earlier study by Crimp *et al.* (2002), used the GRASP model to estimate the impacts of a suite of possible future climates on native pasture growth across Australia. McKeon *et al.* did not use projections of future climate from global circulation models, but instead applied various combinations of (a) an increase in atmospheric CO_2 to 650 ppm, (b) a temperature increase of 3°C and (c) rainfall changes of -30%, -10%, +10% and +20% that were applied uniformly across the continent. They estimated that the response of yearly pasture production to increased CO_2 at 650 ppm would be quite small in south-eastern Australia (0-10% over most of the HRZ and CLZ), with slightly higher (10-20%) response in the lower-rainfall parts of the southeastern CLZ and in south-western Australia. This low response was attributed by McKeon *et al.* (2009) to the low soil fertility that was assumed for the native pastures that were the subject of their analysis. The sensitivity of pasture production to rainfall changes was estimated to be roughly 1.5:1 over most of the continent, with the exception of south-eastern Australia where the assumed nutrient limitation reduced this sensitivity. A 3°C temperature increase was estimated to have a neutral or small positive effect on native pasture production in the south-eastern HRZ, a small negative effect (0-10%) over much of the CLZ and a stronger negative effect in the warmest parts of the CLZ (e.g. Eyre Peninsula).

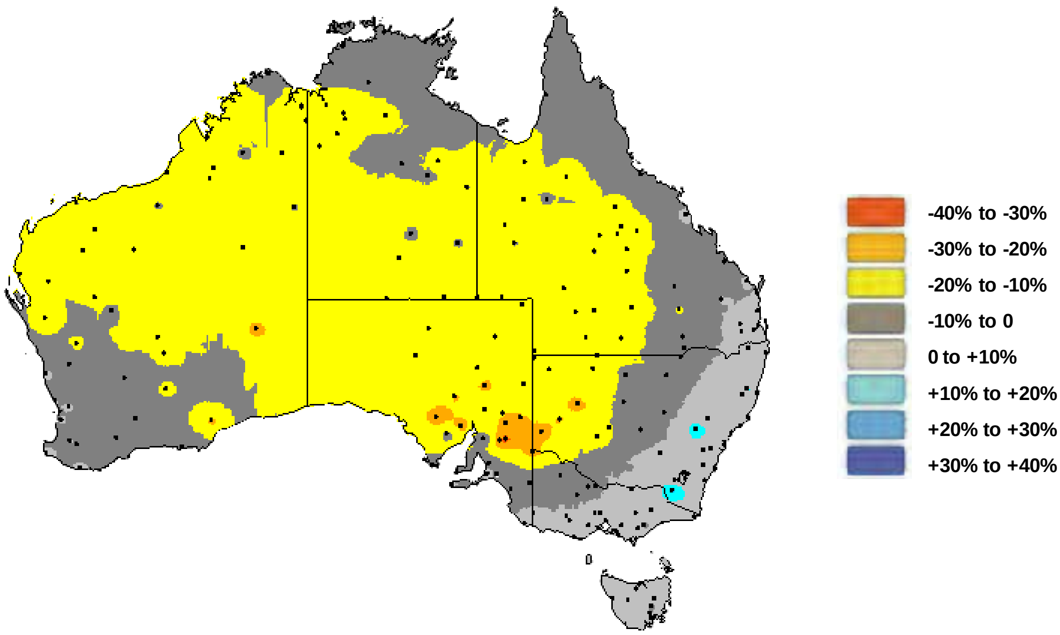

Figure A1.1. Relative changes in annual pasture shoot net primary productivity estimated by McKeon *et al.* (2009) using the GRASP simulation model for a future climate with 650 ppm atmospheric CO_2 concentration, a uniform temperature increase of 3°C and a uniform rainfall decrease of 10%.

A combination of 650 ppm CO_2, 3°C temperature increases and a 10% rainfall decrease (Figure A1.1) can be thought of as a plausible 2070 future in southern Australia. In this scenario, the CO_2 fertilization and rainfall effects roughly cancelled out across southern Australia, so that the overall productivity response was similar to the response to a 3°C temperature increase alone.

Cullen *et al.* (2008, 2009) used the SGS Pasture model to evaluate the impact on pasture growth rates of climate changes projected for a range of Australian locations in 2030 and 2070 by the CSIRO Mark 3.0 global circulation model (GCM) under 3 SRES emissions scenarios (B1, A1B and A1FI). The CSIRO Mark 3.0 GCM predicts modest rainfall changes to 2030 (-9% to +1% depending on location & emissions scenario) and Cullen *et al.* (2008) found correspondingly minor impacts on pasture production. For 2070, however, changes to pasture growth patterns were predicted to be larger. The nature of these changes varied from south to north. At Elliott in Tasmania, 2070 pasture growth was predicted to be higher than current levels despite significant reductions in annual rainfall. At Albany, Wagga Wagga, Terang, Hamilton and Ellinbank, Cullen *et al.* (2008) predicted higher winter and early spring growth rates but a shorter growing season in 2070. At Barraba in northern New South Wales, there was little rainfall change and the balance of pasture composition shifted in favour of C_4 grasses. In irrigation areas, the irrigation water requirement was estimated to increase by up to 10% in 2070, with the greatest increase in northern Victoria.

Cullen *et al.* (2009) also report a modelled CO_2 fertilization response of 24-29% at 550 ppm for C_3 grass-based pastures in southern Australia and 17% at 550 ppm for a mixed C_3/C_4 pasture at Barraba. This estimate of the CO_2 fertilization effect is much higher than that proposed by McKeon *et al.* (2009); the Barraba pasture is of the type considered by McKeon *et al*.

Moore *et al.* (2009) used the GRAZPLAN simulation models to examine impacts of climate change to 2030 on sheep and cattle production systems in the Southern Tablelands of NSW. They considered a much smaller geographic area than McKeon *et al.* (2009) or Cullen *et al.* (2008), but extended their analysis in three directions: (i) by considering the effects of pasture growth changes on the profitability and sustainability of livestock production, (ii) explicitly considering changes to stocking rate and mating date as adaptations to the climate changes, and (iii) attempting to take into account the uncertainty in projected future climates by employing projections from four GCMs. The CSIRO Mark 3.0 model used by Cullen *et al.* (2009) was not one of the four GCMs. Realistic livestock management systems for sheep and cattle were modelled at two locations within the region (Bookham and Goulburn) with differing weather and soils.

Moore *et al.* (2009) found that differences between emissions scenarios (SRES A1, A1B and B1) at 2030 were relatively small, in agreement with Cullen *et al.* (2008). Pasture growth rates in 2030 were projected to increase in winter by all four GCMs when management was held constant. Three of the four GCMs predicted decreases in both autumn and spring pasture growth rates, while one GCM (CCSM 3) predicted little change during these seasons (Figure A1.2). The climate projections from two GCMs implied higher annual pasture growth in 2030 and two lower growth. Overall, the pattern of higher winter growth and shorter growing seasons identified for many sites by Cullen *et al.* (2008) was also found by Moore *et al.* (2009). The key finding of this study, however, was that increased frequency of low ground cover meant that sustainable stocking rates fell – quite sharply for some GCM x emission scenario combinations. As a result, even after adaptation of joining dates, optimal stocking rates under 2030 climate were lower than currently-optimal practice. This was

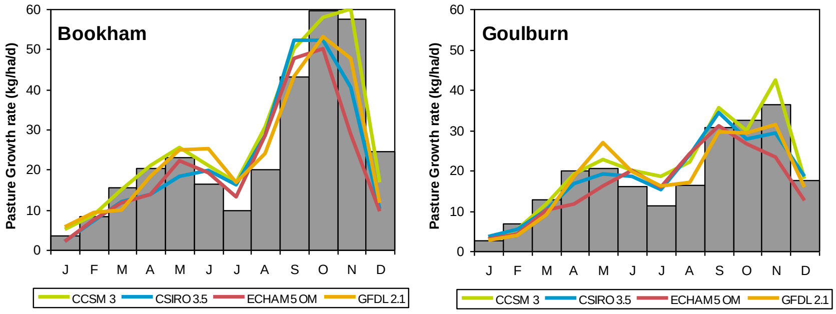

Figure A1.2. Long-term monthly average pasture growth rates projected by Moore *et al.* (2009) for Bookham and Goulburn, NSW, in 2030 for four global circulation models under the A2 emissions scenario. Grey bars show the 1971-2000 average monthly pasture growth rates for comparison.

somewhat compensated by higher weaning rates in sheep production systems, but nonetheless profitability in 2030 was much lower than the magnitude of the pasture growth changes might have suggested.

<u>Research questions arising from this review</u>

Impact of climate change on the livestock industries

- *Size of the CO2 fertilization effect.* The CO2 fertilization effect estimated for southern Australian pastures by the various studies reviewed above ranges from small (<10% at 650 ppm as modelled by McKeon *et al.* 2009) to sizeable (34% at 690 ppm as measured by Lilley *et al.* 2001a). Neither of these studies was intended to reflect the majority of southern Australian pastures. Obtaining a better understanding of the CO_2 fertilization effect – and especially the way it varies with climate and nutrient supply – is a research topic that would repay investigation. As part of such an analysis, it would be important to test the ability of our simulation models to capture the dynamics of the chamber and FACE experiments reviewed in section 3.
- *The possibility of evolutionary response by pastures to changing climate.* Common pasture species such as *Lolium rigidum* show considerable genetic variation in phenology (McLean & Watson 1992) and it may be that natural selection from changing climate will act as an "automatic stabiliser" on pasture productivity. It should be possible to explore at least some aspects of this issue (e.g. the size of the selective pressure) with existing models.
- *Impact of changed climate on livestock water supply.* Livestock water was a significant management issue for some producers during dry years in 2002-08. It may be possible to infer some useful information about likely changes to the water balance of livestock dams – and hence the risk of extended periods of low livestock water availability – from the results of climate change simulations carried out for other purposes.
- *Heat stress.* Moore *et al.* (2008) concluded that "given the size of the projected rise in ambient temperature and the slow rate at which it is expected to increase, it seems likely that adaptation in selected sheep will keep pace with this rise for many years to come". Nonetheless there is scope to use existing models of heat exchange (Turnpenny *et al.* 2000) to evaluate the relative susceptibility of sheep and cattle to heat stress and to check the adequacy of the heat stress equations used in the GRAZPLAN ruminant model.

- *Uncertainty in projections induced by uncertain regional climate projections.* CCASALI clearly cannot rely on the projections of a single GCM. Dealing with the question of how to project impacts while taking the climate projections of different GCMs into account is an active topic of discussion amongst the Australian climate science community. The CCASALI project team should be active participants in this discussion, not least because we are at the front line in communicating with producers in the face of this difficulty.

Adaptations of the livestock industries to climate change

- *Management systems that cope better with shorter, more intense growing seasons.* Identifying such systems is probably the main priority for CCASALI as a whole.
- *The profit-sustainability "feasible space" and how it alters under climate change.* Mokany *et al.* (2010) have described a method for delineating a management space (in their case, combinations of stocking rate and maintenance fertilizer application rate) within which economic and environmental sustainability is likely. Shifts in the boundary of this "feasible space" due to climate, technological or economic changes can show whether broad management strategies such as low-input-low-output are put at risk of becoming unviable.
- *Differential changes in profitability of agricultural enterprises.* The review by Harle *et al.* (2007) raised this issue but the qualitative approach they employed will not assist long-term planning. The need identified by CCASALI for analysing this issue – after taking adaptation of enterprises as well as impacts on them into account – remains.
- *Seasonal forecasts as a means to gradual adaptation.* This idea was quite enthusiastically proposed by both Stokes *et al.* (2010) and Miller *et al.* (2010). CCASALI could evaluate this concept, by comparing the profitability and sustainability of a forecast-responsive producer (under changing and variable climate) to that of one who manages to the long-term trend only. Care would need to be taken to properly cost the prices and costs encountered by a producer who regularly changed stocking rate.
- *The role of C_4 grasses.* A shortening of the main pasture growing season in south-eastern Australia, as suggested by both Cullen *et al.* (2009) and Moore *et al.* (2009), implies a lengthening of the intervening dry seasons, making summer-growing species a riskier proposition. At the same time, however, increasing temperatures should increase the relative attractiveness of C_4 perennial grasses. How will this tradeoff play out in different environments, and will it be better to grow C_4 grasses separately or in mixture with C_3 competitors?
- *The potential value of selecting animals with greater resilience to high temperatures.* This was raised as an option by both Stokes *et al.* (2010) and Miller *et al.* (2010); if heat stress impacts on existing breeds can be better quantified, then the value of selection should be fairly straightforward to estimate taking into account potential tradeoffs in production.

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Appendix 2. Natural selection in southern Australian pastures under climate change: a brief review

Summary

- Evidence from experimental and modelling-based studies indicates that Australian grasslands are likely to undergo significant changes in composition and productivity this century in response to changes in temperature, precipitation and atmospheric CO_2.
- Significant levels of genetic variation are known to occur in both native and introduced pasture species in Australia.
- Variation for a range of climate-relevant traits is known to exist in a range of Australian pasture species. The extent of variation for traits associated with drought and heat tolerance is not known, except in a restricted set of introduced species such as *Phalaris aquatica* and *Lolium rigidum.*
- The heritability and potential response to selection of different climate-relevant traits is not known for any Australian native pasture species. However these traits are known to be heritable and responsive to selection in some introduced species.
- Paleobotanical evidence suggests that climate-driven evolution does not, in general, result in the broadening of species' physiological niches and that changes in species distributions broadly track changes in climate.
- Theoretical and contemporary evidence indicates that local adaptation could potentially alleviate some of the adverse effects of climate change, especially in range-core areas where plant population sizes and genetic variation are large.
- We suggest that a targeted research effort based on quantification of heritable variation for a range of traits in species representative of different key functional groups would help determine the evolutionary capacity of key pasture species, and would provide pointers for better management of southern pastures under future climate change.

In a general sense, how might pastures in Australia (both native and sown) alter under the impact of a changing climate?

Here we review the potential impacts of climate change on the Australian pastures, rangelands and grasslands. We specifically consider the roles of temperature, precipitation and elevated atmospheric CO_2 on grassland composition and structure; evolutionary and genetic components of change are specifically addressed below.

The composition and structure of Australian pastures, like grassland ecosystems globally, varies markedly in response to a wide range of factors including soil type and nutrient levels, climate, topography, disturbance regime, and the presence of invasive species. Significant changes in the composition of grasslands in southern Australia have already occurred over the past 200 years, with tall warm-season perennial tussock grasses being replaced by short cool season perennial or introduced annual species, depending on grazing intensity, fertiliser use, fire frequency, and cultivation (Moore 1970; Garden *et al*. 1995). State and transition models describing these compositional shifts (Garden & Bolger 2001) document that many Australian grasslands and pastures are prone to change when faced with altered abiotic and biotic conditions.

Several lines of evidence suggest that climate change will drive significant, broad-scale changes to Australian pastures. First, several key functional groups of grassland species show marked distributional responses to climate: for example C_3

species tend to dominate regions characterised by wet, cool springtime conditions while C_4 species (Osmond 1987) are prevalent in more warmer regions with dominant summer rainfall (Johnston 1996). Similar compositional patterns exist at smaller spatial scales (Williams 1979; Johnston 1996). Second, extreme climatic conditions such as drought are known to dramatically affect grassland species (Godfree *et al*. 2010), especially under grazing (Hutchinson 1992), while phenological change has been observed in subalpine species subjected to experimental warming (Hoffmann *et al*. 2010). Third, results from most experiments globally indicate that grassland systems undergo significant composition change when exposed to simulated climate change and CO_2 enrichment (Grime *et al.* 2000; Zavaleta *et al*. 2003) and results of pasture modelling generally support this view (e.g., Howden *et al.* 1999; although see Grime *et al.* 2008). Finally, Australian rangelands have responded significantly to past climate change events (Cupper 2005).

Predicting the specific patterns of change in most southern Australian pastures in the absence of any significant *in situ* experimental evidence remains difficult. This reflects the complex nature of interactions between water availability, precipitation, soil nutrient levels, temperature, and CO_2 concentration (Tubiello *et al.* 2007). Invasive species, disease and herbivory, also affected by climate change, may also play an important role in many systems. Furthermore, many of the expected improvements in pasture production and performance resulting from CO_2 enrichment (see below) may be offset or negated by declining rainfall, a variable that exhibits wide variability in global circulation model projections for Australia.

The most detailed investigation of the changes expected in Australian rangelands is reported by McKeon *et al.* (2009) (see also Howden *et al.* 1999). Using a model-based approach, they show that pasture production across Australia is likely to rise as a response to elevated CO_2, but decline with rising temperature and declining rainfall. Depending on the specific combination of changes to CO_2, temperature and rainfall, future pasture production estimates range from 45% below current levels to 62% higher. Realistic estimates for 2070 (650 ppm CO_2; +3°C, -10% rainfall) predict a 15% decline in productivity across Australian rangelands nationwide, but estimates are highly contingent on changes in rainfall regimes. The authors note that given the strong effects of CO_2 and rainfall on pasture performance many uncertainties remain in predicting the behaviour of rangelands in response to climate change (McKeon *et al.* 2009). However, the models presented suggest that native pastures of temperate southeastern and southwestern Australia, where soil fertility plays a more important role in limiting production, are likely to be less susceptible to climate change than semi-arid or arid rangelands, with productivity changes in the order of -10% to +10% depending on the specific climate scenario.

Little is known about the specific manner in which different pasture communities are likely to respond to climate change. In a general sense, rising atmospheric temperatures and reduced winter precipitation might be expected to increase the proportion of southern Australia that lies under subtropical influence (http://climatechangeinaustralia.com.au). Semi-arid and arid zones may also expand in some areas. C_4 species, which, being more water-use efficient than C_3 species, dominate in warmer and drier parts of Australia (Williams 1979; studies reported in Johnston 1996) would probably benefit (relatively) from declining winter rainfall and rising temperatures in cooler, wetter regions while cool-season annual and perennial species may decline. A shift towards growing subtropical species is now being advocated as far south as the central western slopes of NSW, a trend likely to continue into the future. In cooler, wetter tablelands regions local reorganisation of the dominance relationships among C_3 species is likely.

As mentioned, rising atmospheric CO_2 is likely to be a key driver of changes to many ecosystem processes. All else being equal, CO_2 enrichment is likely to increase the productivity of vegetation systems (Drake *et al*. 1997; Howden *et al.* 1999; Tubiello *et al*. 2007; McKeon et al. 2009), including grasslands and rangelands (Jongen and Jones 1998; Morgan *et al.* 2001), with growth and productivity gains likely higher in C_3 species than in C_4 species (Poorter 1993; Tubiello *et al.* 2007). However, differences between C_3 and C_4 species may be less than is often suspected (Morgan *et al.* 2001) due to the complex nature of CO_2-precipitation-temperature-soil interactions in most plant communities. Elevated atmospheric CO_2 will also probably favour increased incursion of weedy weeds and shrubs into grasslands and rangelands, because woody species have metabolic processes, carbon allocation regimes and root characteristics that are more responsive to elevated CO_2 than grasses (Morgan *et al.* 2007). Changes to carbon cycling and carbon pools (Hungate *et al*. 1997) and alteration of the responsiveness of plant species to heat and drought stress in response to CO_2 enrichment (Barker *et al.* 2005) can also be anticipated.
Finally, under climate change the frequency and severity of extreme events is also expected to increase in many parts of Australia. An increase in the severity of droughts and heatwaves would likely have a significant impact on the production and composition of Australian pastures, since recent work has shown that native grass species can be strongly affected by extreme events (Godfree *et al*. 2010). The greatest effects would most likely be evident in marginal environments where species exist towards their physiological limits (Hampe & Petit 2005), and over time, this could result in loss of species from these pastures.
Overall, the available evidence indicates that many southern Australian pastures are likely to undergo substantial compositional and structural change in response to climate change. This is not surprising, since grasslands are well known to respond in often dramatic fashion to both short – term (Godfree *et al.* 2010; Weaver & Albertson 1944) and long-term (Collatz *et al*. 1998; Cupper 2005) atmospheric conditions.

<u>What is the evidence that genetic variation in pasture species may give them the capacity to evolve under a changing climate in a practical situation (i.e. when grazed)?</u>

In this section we review the evidence for genetic variation in Australian pasture species and discuss the factors that underpin the capacity of species to respond to climate change via genetic advance for advantageous traits. We discuss the evidence for native and introduced pasture species separately as data availability varies greatly between the two groups.

Overview

Climate projections for southern Australia suggest that most plant species and communities in southern Australia will likely face warmer temperatures, reduced water availability (especially in winter), higher evaporation, increased transpirational demand, and an increase in the frequency and severity of heatwaves and drought. For the purposes of this section we therefore assume that the dominant selection pressure arising from climate change will be on traits linked to these stresses. However, we note that for Australian pastures, knowledge of the identity of the specific traits that are likely to be relevant to climate change remains extremely limited.

Plants can respond to climate change via evolution for advantageous traits only under the following specific circumstances. Within-population genetic variation must exist for traits that result in differential fitness of individual plants, and this genetic variation must be heritable. Selection must also act on relevant traits, resulting in increased frequency of advantageous alleles in the population, and genetic advance must occur at rates similar that of climate change itself.

Genetic variation

Native species

Presently, little information is available concerning the level of inter-population and intra-population variation for traits related to growth, water use, productivity and phenology in extant populations of native Australian pasture species. This is unfortunate given that native tussock species are keystone components of many Australian pastures, especially in broadacre grazing and rangeland assemblages. Perhaps the most well studied species has been the perennial C_3 tussock grass *Austrodanthonia caespitosa*, for which variation in phenology, reproduction and growth has been quantified in populations collected from arid to temperate environments (Hodgkinson and Quinn 1976, 1978). These studies indicate that genotypic differentiation for vernalisation response, inflorescence development rate, day length for floral initiation, optimum temperatures for growth, and growth rate is present in populations of *A. caespitosa.* This work also demonstrated significant intrapopulation variability in reproductive time, with southerly populations exhibiting greater variability.

Variation for similar traits has been observed in *Themeda australis* (Groves 1975; Evans and Knox 1969), which has a complex cytology in Australia (Hayman 1960). Other studies, however, have shown that ecotypic differentiation does not exist for germination characteristics in some populations of this species (Groves *et al*. 1982). Waters *et al*. (2003) demonstrated that significant intraspecific variation and ecotypic differentiation exists among a range of native grassland species from inland NSW and Queensland for traits such as plant height, and basal diameter, and that within-population variation was also significant in some species. In a very large study (Garden *et al*. 2005; Norton *et al*. 2005; Waters *et al*. 2005) conducted across multiple biomes in south-eastern Australia, comparisons of different genotypes within several native species including *Elymus scaber* and *Microlaena stipoides* revealed significant interpopulation-level differences in survival, recruitment and herbage production. Interestingly, however, Waters *et al.* (2005) argued that interpopulation variation in these traits may be related to genetic drift rather than local adaptation. Fine scale trait variation, ecotypic differentiation or genetic divergence has also been observed in *Microlaena stipoides* in northern NSW (Magcale-Macandong 1994), *Danthonia* spp. (Lodge & Shipp 1993) and *Poa hiemata* in the Australian Alps (Byars *et al*. 2009).

Collectively, the evidence suggests that significant interpopulation ecotypic differentiation exists in a broad range of grass species from southern and eastern Australia. Within-population variation for a range of traits associated with growth and reproduction is also known to exist in some species. This is consistent with the observation that a high proportion of Australian grasses are self-pollinating or lack self incompatibility (Groves and Whalley 2002), since in general interpopulation differentiation is expected to be higher in self-fertilising than outbreeding species. It therefore appears reasonable to conclude that at least some, and probably most native pasture species have sufficient genetic variation for evolution to act on under climate change.

Introduced species

In southern Australia, economically important introduced pasture species occur in a wide array of functional groups. Palatable, desirable species include an array of annual grasses (e.g., *Lolium rigidum*, *Bromus* spp., *Avena* spp.), perennial grasses (e.g., cocksfoot, *Phalaris*, *Lolium perenne*, *Festuca arundinacea*), and both annual and perennial legumes (e.g., *Medicago* spp., *Trifolium* spp.). Other leguminous genera have also been proposed as having grazing potential in this region (e.g., *Vicia* spp., *Astragalus* spp.; Cocks 2001). A range of species that may be desirable in certain pasture situations also occur; these include perennial forbs (e.g., *Hypochoeris radicata*, *Plantago lanceolata*), annual forbs (*Trifolium* spp.) and perennial grasses (e.g., *Nassella neesiana*, *Eragrostis curvula*). In the case of *Plantago* and *Eragrostis*, desirable cultivars have been developed for commercialisation (Johnston 1989; Rumball *et al.* 1997). Here we briefly review evidence for genetic variation among a selection of the more important of these species.

Annual introduced grasses are known to exhibit significant genetic variation both in Australia and worldwide. For example, annual ryegrass, which is an important forage species in drier parts of southern Australia, is known to show quantitative variation for herbicide tolerance (Heap & Knight 1990), which evolves rapidly under field conditions. Variation in phenology, flower induction and dormancy release which, for an annual species, are likely to be important under climate change, have been observed in Australian accessions of *L. rigidum* (Cooper 1960; Steadman *et al.* 2003), and adaptation of *L. rigidum* to Australian climatic conditions has been observed over large spatial scales (Gill *et al.* 1996). Variation and local adaptation has also been observed for dormancy- and growth-related traits in *Bromus diandris* in southern Australia (Gill *et al*. 1984), while ecotypic differentiation has been recorded in *Avena* spp. in NSW and Queensland (Whalley & Burfitt 1972). These data indicate that introduced annual grasses in Australia are likely to exhibit significant large- and small-scale genetic variation for climate-relevant traits, thus increasing the likelihood of evolution under selection pressure.

Variation for drought-related traits is also well documented in other introduced plant groups. Drought tolerance, summer dormancy and other traits exhibit significant variation in Australian and Mediterranean accessions of *Phalaris aquatica*, *Dactylis glomerata, Lolium perenne* and *Festuca arundinaceae* (Oram 1984, Reed 1996, Piano *et al.* 2004; Norton *et al.* 2006; Culvenor 2009). Genetic and phenotypic variation has been observed for numerous traits (e.g., summer moisture stress adaptation and growth) in *Trifolium repens* (white clover; Lee *et al.* 1993; Jahufer *et al*. 1999), and also in other species including strawberry clover (McDonald 2008). Seed dormancy (hardseededness) and phenology vary in the annual species *Trifolium subterraneum* (Smetham 2003), and numerous cultivars of *Medicago polymorpha* and *Medicago truncatula* are now sown in Australia. Ecotypic or cultivar-based differentiation has also been recorded in overseas collections of *Hypochoeris radicata* (Becker *et al.* 2008) and *Plantago lanceolata* (Rumball *et al.* 1997). While far from comprehensive, these case studies suggest that many desirable introduced species in Australia are likely to exhibit significant within-and between-population variation for climate-relevant traits.

Finally, numerous introduced weedy species that severely curtail pasture production are also known to be genetically variable within Australia. Such species include *Echium plantagineum* (Paterson's curse, Piggin & Sheppard 1995), *Hypericum perforatum* (St John's wort; Campbell *et al.* 1992), *Nassella trichotoma* (serrated tussock; Hussaini *et al.* 1999), and *Nassella neesiana* (Chilean needlegrass, Britt *et al.* 2002). This is consistent with the observation that invasive species often exhibit significant genetic variation and can undergo rapid adaptation in new environments (Prentis *et al.* 2008).

Heritability and potential response to selection

Virtually no research has been conducted on the heritability and response to selection of traits relevant to climate change in any native Australian pasture species. In our opinion this is probably the single largest knowledge gap relevant to predicting the evolutionary response of Australian pastures to climate change. Indeed, the extent of heritable variation for traits associated with water use efficiency, growth and other key physiological and demographic traits is also unknown for most introduced pasture species that have a history of breeding and adaptation in Australian agriculture.

Native species

One key problem is that Australian native grasses have little history of breeding and selection. However, lines of *Austrodanthonia richardsonii* and *A. linkii* have been commercialised based on selection for seed retention and production (Lodge & Schipp 1993). *Microlaena stipoides*, a common species in cool, wet environments, has undergone selection for morphology, flowering time and seed production. Other traits that appear to demonstrably respond to selection include cool-season leaf production and dry matter yield (in *Astrebla lappacea* and *A. pectinata*), stem height (in *Themeda australis*), and culm formation (in *Bothriochloa macra*). Breeding and selection of these and other native Australian grasses is reviewed in Lodge (1996). Response to selection for grazing tolerance, productivity and response to soil fertility has been observed on decadal scales under natural settings in *Austrodanthonia* spp. and *M. stipoides* populations (reviewed in Oram & Lodge 2003). These authors suggest that the evolutionary potential of Australian native grass populations has been frequently overlooked and that many characteristics of pasture grasses in general are as responsive to selection as those in crop or introduced pasture plants.

Introduced species

The international literature indicates that many traits potentially under selection in a changing climate exhibit heritable variation in both crop and pasture species. For example, water use efficiency has a moderately to strongly heritable basis in some populations of lucerne (Ray *et al.* 1999), cotton (Condon & Richards 1992; Stiller *et al.* 2005), tall fescue (Johnson *et al.* 2008) and crested wheatgrass (Asay *et al.* 1998). Evolutionarily important traits such as salt tolerance (Ashraf *et al.* 1986), grass seed awn length (in fire-prone systems; Garnier & Dajoz 2001), frost tolerance (Caradus *et al.* 1990), hardseededness and flowering (Ramakrishnan *et al.* 2004), and vegetative yield, seed yield, crude protein, and plant height (De Araújo & Coulman 2002) also have a significant heritable basis in different plant groups. Breeding systems and facultative allocation to cleistogamous versus chasmogamous flowers is known to be heritable (in the broad sense) in *Danthonia spicata* (Clay 1982); cleistogamy is common in Australian grasses (Campbell 1983).

Heritable variation and response to selection have been investigated in several key species within an Australian context. The ability of *Phalaris aquatica* to re-sprout from buds at the basal nodes of tillers following summer rain has been shown to have a heritable basis (Culvenor 2009), with narrow-sense heritabilities of approximately 0.4 (Oram 1984). This mechanism, which improves the ability of *Phalaris* to withstand drought, is a likely candidate for selection under climate change. Drought tolerance based on summer dormancy also appears to be responsive to selection in cocksfoot (*Dactylis glomerata*; Piano *et al.* 2004). Seed dormancy in *Lolium rigidum* is known to have a genetic component and reduced levels of dormancy can be selected for (Goggin *et al.* 2010), while evolutionary adaptation has been observed in *Trifolium subterraneum* (Nichols 2004).

Overall, these data suggest that many Australian pasture species likely possess some degree of evolutionary potential under climate change. However, this conclusion is based largely on inference as evidence for selection and evolution exists for a very few Australian pasture species. In the absence of clear experimental data obtained from Australian settings we must conclude that the rate of evolutionary responses to climate change in different parts of species' ranges, the specific responses of Australian species, and the traits involved are not well understood.

The role of grazing

As noted above, grazing has apparently led to genetic changes in populations of native grasses in southern Australia over a relatively short timescale (Oram & Lodge 2003). On the other hand, grazing has been responsible for large-scale replacement of warm season native grasses with cool-season perennial and annual species over much of southern Australia over the past 200 years. Presumably grazing practices that adversely affect the size and reproduction of plant populations (e.g. Hodgkinson 1976) would reduce the capacity of associated species to evolve in response to climate change. Historical evidence indicates that taller, tussock-forming or caespitose grasses do not tolerate grazing as well as shorter, stoloniferous species with protected growing points (Garden & Bolger 2001), and so the former species would likely suffer relatively impaired capacity to respond to climate change via evolution. However, variation for these traits exists in some species that are potentially at risk from the effects of grazing under climate change, such as *Themeda australis* (see Oram & Lodge 2003). Management regimes that minimise grazing during reproduction may improve the evolutionary performance of such species. Grazing practises (e.g., overgrazing) that advantage less palatable or weedy species such as *Nassella trichotoma* and *Eragrostis curvula* at the expense of more palatable species could also increase both the dominance and evolutionary potential of weedy species in southern pastures. At present however the interactions between future climate change, grazing and evolution are unclear.

<u>Might pastures have the capacity to change at the same pace as the climate?</u>

Numerous studies have demonstrated that local adaptation for advantageous traits can develop in plant populations in response to changing environmental conditions on relatively short (generational) timeframes (see Bone & Farres 2001; Davis *et al*. 2005); rapid ecotypic differentiation in Australian lines of *Trifolium subterraneum* (Nichols 2004) is a case in point. Consequently, some authors argue that evolution may play a significant role in mitigating some of the adverse effects of climate change on plant populations (e.g., Davis *et al.* 2005). Indeed, evidence for rapid selection for environment-linked traits in natural plant populations (e.g., Antonovics *et al*. 1971) challenge the traditional Darwinian view that evolution is a slow process, with significant changes accruing only over long periods of time.

In a recent review, however, Gienapp *et al.* (2008) demonstrate that unambiguous experimental evidence for a clear role for microevolutionary adaptation in mitigating the negative effects of climate change remains scarce. Parmesan (2006) arrived at the same conclusion from paleophytogeographical evidence, noting that past episodes of major climate change (such as Pleiostocene glaciation) did not stimulate major evolution in plant taxa, and that most species appear to have shifted their geographic ranges to track changes in climate. Indeed, there is little evidence that the absolute physiological tolerances of species shift in response to climate change, or that novel genotypes develop that facilitate the movement of species into new climatic zones (Parmesan 2006, papers cited therein). Indeed, Huntley (2007) argues that while evolutionary advance for some phenotypic traits may occur, evolutionary adaptation is unlikely to be an important driver of species' responses to climate change in the coming century, and that habitat fragmentation and the projected speed of climate change could severely curtail what evolutionary potential does exist.

Although the debate continues, these lines of evidence collectively suggest that successful species will be restricted to those that have sufficient levels of genetic diversity to cope with rapid climate change (Huntley 2007). Evolutionary theory suggests that this is more likely to occur in environments that are experienced by the largest number of individuals within a population (i.e., towards the centre of species' ranges) (Bridle & Vines 2006), and may be more likely in populations of introduced or invasive species, which often exhibit rapid local adaptation (Prentis *et al*. 2008). Evolutionary change in response to shifts in climate are probably less likely to occur in marginal environments where plant populations have had a long history of selection for climate-related traits and hence a narrow genetic base (Bridle & Vines 2006). In such habitats plant species may often be characterised by the ability to persist for long periods of time without recruitment, instead relying on longevity, persistent seedbanks (Hampe & Petit 2005) and probably phenotypic plasticity. These traits have been linked to a reduction in the ability of plant species to evolutionarily respond to contemporary selection regimes (Silvertown 1988). Thus, extinctions are more likely to occur when species and populations that occur in marginal environments are moved outside of their physiological niches.

Potential future work

As discussed above many knowledge gaps exist in the literature associated with evolutionary and ecological responses of Australian pastures and grasslands to climate change. We suggest that the key knowledge gaps that should be addressed in future work are:

1. What is the level of heritable genetic variation in native and introduced species that represent the key functional plant groups in pastures and grasslands?
2. What are the traits that are likely to be selected under climate change?
3. Do core and range-edge populations of native and introduced species differ in evolutionary potential?
4. Giving any lack of adaptive potential, which grazing systems are most likely to be placed at risk by climate change?

Here we propose a research plan that is aimed at filling these knowledge gaps as efficiently as possible. It involves 3 key stages conducted over 3 years aimed at providing a preliminary determination of the key traits selected for under climate change (warmer and drier conditions) and the extent of heritable genetic variation in these traits.

Stage 1: Identification and collection of key pasture species

Time: 12 months

Since little is known of the evolutionary potential of pasture species in Australia, the first stage of the research plan would be to identify representative species from each of the main plant functional groups in SE Australian pastures, and to then make collections of core and range-edge populations for each species. We would focus on species that crucially underpin grazing operations in this region and would span the key bioregions of southern Australia. Possible species and groups could include:

Functional group	Species	
Native perennial grass	*Bothriochloa macra* *Microlaena stipoides* *Austrostipa spp.*	*Austrodanthonia spp.* *Themeda australis*
Introduced perennial grass	*Lolium perenne* *Phalaris aquatica* *Dactylis glomerata*	*Festuca arundinacea* *Pennisetum clandestinum*
Introduced annual grass	*Hordeum leporinum* *Lolium rigidum* *Vulpia sp.*	*Bromus molliformis* *Avena barbata*
Introduced annual forb	*Trifolium subterraneum* *Medicago truncatula*	*Arctotheca calendula* *Echium plantagineum*

Functional group	Species	
Introduced perennial forb	*Medicago sativa* *Trifolium repens* *Carthamus lanatus*	*Acetosella vulgaris* *Hypochoeris radicata*
Invasive grass species	*Nassella neesiana* *Nassella trichotoma*	*Hyparrhenia hirta* *Eragrostis curvula*

These species represent many of the key, naturalised or native pasture species of southern Australia. Ideally, we would collect two range-edge and two range-core populations from each species included in the study. It would probably be practical to survey one to two of the most important species in each group, but numbers would depend on funding availability.

Stage 2: Within-population trait identification and evaluation of genetic variation

Time: 24 months

This stage quantifies the genetic variability in traits that are likely to be subjected to significant selection pressure under climate change. We think that a study aimed at identifying genetic variation for flowering time, dehydration tolerance and avoidance, water use efficiency, heat tolerance, rooting depth and resource allocation in the subset of important pasture species identified above would be an essential part of any research programme. Comparison of range-core and range-edge populations within species would provide key information on the traits that are likely to be important in a warming, drying environment.

Stage 3. Preliminary assessment of selection potential

Time: 24 months

The final stage of the work would involve initial quantification of the potential response to selection in populations of key grassland species. Species and population selection would be based on results of projects 1 and 2 above, and would include only species for which significant variation in climate-related traits was observed. Experiments would be conducted using field and/or glasshouse experiments with the objective of estimating heritability for key climate-related traits. This would address the knowledge gaps raised in this review.

Timeline & resources

As mentioned, the proposed project would run over 3 years, with overlapping of the different stages.

Research phase	Year 1		Year 2		Year 3	
Stage 1						
Stage 2						
Stage 3						

The level of resourcing would depend on the number of species and functional groups chosen, the number of traits investigated, and the complexity of estimating heritability. A “first cut” approach might involve a small number of highly important species (~5-10) assessed for a restricted set of traits, and would require ~1 technical officer and modest contributions from 1-2 scientists. A comprehensive study would require 1.5-2 technical officers and significant contributions from 2-3 scientists. Operating costs would include some travel and glasshouse space, and some minor consumables.

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Appendix 3. Effectiveness of a range of grazing system adaptations in ameliorating the impacts of shorter growing seasons

Introduction

Modelling studies of pasture growth based on projections of future climate by different global circulation models (GCMs) commonly predict shorter growing seasons in southern Australia with higher winter growth rates. We have therefore undertaken a simulation study to identify potential strategies that may be adopted by managers of sheep enterprises in order to adapt to the effects of shorter, more intense growing seasons (SIGS).

This Appendix describes the development of a method for modifying historical weather records so that growing seasons start later and end earlier, and the use of this method in conjunction with simulation modelling to explore the effect of alternative management strategies on profitability of a sheep grazing enterprise subjected to shorter growing season, at a range of locations across southern Australia.

Methods

Locations

To identify advantageous management strategies that were applicable in a number of regions and under diverse conditions, we selected multiple locations for analyses. Locations were selected to fall within the seven ABARE regions with the highest total value of production from sheep enterprises (see the financial tables at www.abare.gov.au/interactive/agsurf/tables/08_09/Financials_TBL.xls). Within each region a single location was selected based on the availability of readily-available information about soils and pastures. The locations that were chosen were Hamilton (Vic), Goulburn (NSW), Wagga Wagga (NSW), Cowra (NSW), Katanning (WA), Lucindale (SA) and Mt Barker (WA)

Grazing system details and initial conditions

Grazing systems at each location were modelled using the GrassGro decision support tool (Moore *et al.* 1997). A common livestock enterprise (Merino ewes producing first-cross lambs) was simulated at all seven locations in order to simplify comparisons across locations. This particular system was selected as it is employed widely across southern Australia in both the high-rainfall and cereal-livestock zones. The baseline enterprise consisted of medium Merino ewes (standard reference weight 50 kg) crossed with Dorset rams, with lambing on 21 April and weaning on 21 July. Ewes were mated for the first time at 18 months of age. Excess young ewes and wethers were sold between 1 September and 31 January (i.e. aged 18-40 weeks) once their average weight change over the preceding week fell below zero. Maintenance feeding was performed at any point during the year when the average condition score of animals in an age class fell below 2.0. Ewes and any remaining lambs were shorn each 30 November. Six-year-old ewes were sold on 30 November and immediately replaced by purchased ewes (17 months, condition score 3.0).

Both autumn and spring lambing dates were considered while these modelling analyses were being designed. In the end we chose to use a common (autumn) lambing date across all locations rather than location-specific lambing dates. Even though autumn may not be the most common choice of lambing date at all of the seven locations, it would be practiced by some graziers within each region. Also, preliminary simulations indicated that, for the cost and price assumptions used here,

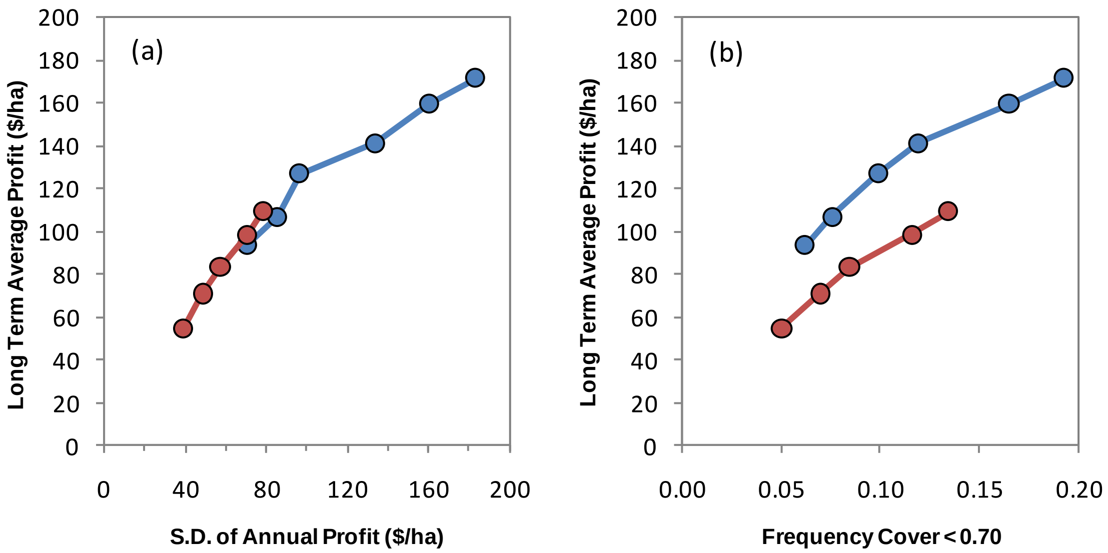

Figure A3.1. Profit versus risk in Merino ewe grazing systems at Wagga Wagga. (a) Long-term average profit versus long-term average standard deviation of annual profit at and (b) long-term average profit versus the frequency with which ground cover i below 0.70. Blue curves are for ewe grazing systems with April lambing and red curves are for July lambing. Points are mean values of 30 years simulated using historical weather records from 1970-1999 at a range of different stocking rates.

the long-term expected profitability of autumn-lambing systems was higher at all seven locations at equal levels of frequency of low ground cover (see Figure A3.1 for an example). On balance, therefore, it was decided to use a common (April) lambing date.

The costs and prices given in Appendix 1 for medium-wool Merino ewes were used to compute financial returns. Pasture management costs were based on fertility scalars, which in turn were determined by incremental fertiliser applications as described by Quigley *et al*. (2003). All fertilisers were assumed to be diammonium phosphate and were priced at $500 per tonne following values given by the Fertiliser Industry of Australia Incorporated. Overhead costs of $100/ha were assumed at all locations.

For each grazing system and adaptation option considered, an “optimal sustainable” stocking rate was then identified as that rate which maximized long-term profit, subject to the constraint that ground cover (averaged over the farm) should be less than 0.70 on no more than 7% of days over a 30-year period. This rate was found by simulating stocking rates in increments of 0.5 or 1.0 ewes/ha and selecting from these rates the one that met the criterion.

Manipulating baseline weather records to produce shorter growing seasons

We produced artificial weather records that would consistently shorten growing seasons but produce greater winter growth rates when simulated using GrassGro. To make the contraction of growing season uniform across sites, weather records were iteratively modified so the reduction in total annual net primary productivity (NPP) from baseline conditions was approximately 10%. The general approach was to (i) “squeeze” the rainfall events corresponding to each year’s growing season into a smaller period of time, while carrying the variation in temperature and radiation corresponding to each sequence of wet and dry days along with it; (ii) increase temperatures by a fixed amount; and (iii) increase the atmospheric CO_2 concentration.

The following describes the procedure used to modify baseline weather records to produce SIGS for each site in attempt to produce artificial weather data that were representative of 2030 conditions.

1. Baseline weather records were obtained as Patched Point Datasets (PPDs) from the SILO database (http://www.longpaddock.qld.gov.au/silo, verified 25 October 2010).
2. Using the initial conditions specified and optimal stocking rate for historical weather conditions (identified in preliminary simulations), the earliest, median and latest dates of 'start' and 'end' of growing season were determined from the 30 years simulated at each site.
3. A function was defined that defined the number of days a given day-of-year should be shifted in time so as to shorten the growing season. This function increased linearly from zero on the day-of-year of the earliest growing season start until the median growing season start, then declined linearly to zero on the day-of-year of the latest growing season start. Similarly, the function decreased linearly (i.e. a negative shift in time) from zero on the day-of-year of the earliest growing season end until the median growing season send, and then increased linearly back to zero on the day-of-year of the latest growing season end. Where possible break and end contractions were made uniform but within the constraint that no original day from the baseline was mapped to more than six days on the SIGS weather record.
4. Cubic splines were fitted to long-term average records of maximum and minimum daily temperatures and the clearness index (ratio of radiation at the ground surface to radiation reaching the top of the atmosphere) for wet (rainfall greater than zero) and dry days.
5. Using the long-term values computed in step 4, weather anomalies were computed.
6. All weather anomalies were mapped to an interval defined by the shifting function determined in step 3. This time interval was greater than 1 day when the shifting function was increasing and vice-versa.
7. Daily maximum and minimum temperatures for the SIGS weather records were calculated long-term average for the shifted date plus the temperature anomaly plus 2^{o}C. Uniformly increasing the temperature on all days of each year enhances pasture growth rates but also hastens phenological development leading to earlier senescence, producing the desired effect of shorter but more intense growing seasons.
8. Daily rainfall and clearness index data for the SIGS record were determined by summing or averaging the result back into daily intervals. Maximum and minimum temperatures for the SIGS record were determined from the baseline day that contributed the largest share to the transformed day.
9. Finally, SIGS records were produced by adding the anomalies back to long-term historical records. Modified Penman-Monteith equations as described by the FAO (Allen *et al.* 1998) were used to compute corresponding daily vapour pressure and pan evaporation values.

All simulations of SIGS were run with an assumed atmospheric CO_2 concentration of 450 ppm. This higher CO_2 concentration increased the modelled radiation and water use efficiencies during the growing season.

There is no generally-accepted method for defining the start and end of growing seasons. In this work, the start of each growing season was defined as the date when total available green dry matter (AGDM) became greater than 500 kg/ha and daily pasture growth rates were 1 kg/ha or greater. The end of each growing season was defined as the date when total AGDM became less than 100 kg/ha. End dates were allowed to occur as late as 31 March of the following year (whereupon the following growing season was initiated if ‘start’ conditions were also satisfied).

By design, the SIGS weather time series had the same total rainfall in each year of the record (and hence the same rainfall variability), but with rainfall concentrated into a shorter period in autumn through to spring. Temperatures and evaporation rates were higher and radiation amounts were generally similar.

The maximum shifts applied to growing season start dates ranged from 10.5 d at Wagga to 52 d at Katanning, and shifts applied to end dates ranged from 5 d at Hamilton to 38 d at Katanning (Table A3.1).

Table A3.1. Median start and end dates identified from growing seasons simulated at the seven sites examined, and corresponding shifts applied to median dates to reduce total net productivity by approximately 10%.

Site	Median start of growing season	Shift applied to start dates (days)	Median end of growing season	Shift applied to end dates (days)
Hamilton	18 Feb	30	31 Dec	5
Goulburn	26 Mar	25	23 Dec	25
Wagga	28 Apr	10.5	24 Nov	10.5
Katanning	13 May	52	17 Nov	38
Cowra	7 Apr	27	17 Dec	27
Lucindale	26 Apr	40	22 Jan	26
Mt Barker	30 Apr	26	31 Dec	30

Adaptation options

The adaptation options to be tested were determined via a survey of state-based managers, industry representatives and scientists in the *Southern Livestock Adaptation 2030* program. Participants were asked to rank management changes in the order they believed that would be most likely to be implementable as adaptation options. This approach enabled a prioritisation of strategies that would have the greatest likelihood of being implemented by producers in the short-term.

Adaptation strategies examined included:

1. *Confinement feeding*: Between 1 November and 1 August in the following year, all livestock were removed from paddocks when total available dry matter fell below a threshold mass and were put back onto fields when AGDM became greater than 400 kg/ha. Sheep in feedlots were fed a supplement that was sufficient to maintain live weight *ad libitum* (as ewes were generally pregnant during confinement feeding, the quality of this supplement was quite high). No confinement feeding was performed under baseline conditions. Three variants of this option were examined:
   - start feeding when AGDM fell below 2000 kg/ha;
   - start feeding when AGDM fell below 1500 kg/ha;
   - start feeding when AGDM fell below 500 kg/ha.

2. *Joining time and age:* Several combinations of joining time (1 Nov and 1 Dec) and age at first joining (6, 18 or 30 months) were considered, following Young *et al*. (2010) who showed that modification of joining times and ages of first-cross lamb enterprises had large effects on profitability. Conception rates of single and twin lambs were adjusted according to joining time and latitude of each site using the equations given by Freer *et al.* (1997), assuming a joining period of 6 weeks. The base scenario used 1 Nov mating and first joining at 18 months. Five variants were examined:

- 1 Nov mating, first joining at 6 months;
- 1 Nov mating, first joining at 30 months;
- 1 Dec mating, first joining at 6 months;
- 1 Dec mating, first joining at 18 months;
- 1 Dec mating, first joining at 30 months.

3. *Earlier-maturing annual grasses:* The effect of adding early-maturing annual grasses to the pasture sward was also examined, to test the hypothesis that production of more forage at earlier times of the growing season via an earlier-maturing genotype would extend the period of adequate cover during summer-autumn and also reduce the need for supplementary feeding. Two varieties of annual grass were considered:
   - the standard "early annual grass" parameter set, corresponding approximately to barley grass (*Hordeum leporinum*)
   - a hypothetical "very early annual grass" that was constructed by adjusting the parameter set for "early annual grass" to make the onset of reproductive growth, flowering date and developmental senescence earlier.

4. *Increasing pasture fertility:* Modifications to pasture fertility were examined since future climates will effect plant tissue concentrations of photosynthetic enzymes (primarily protein dilution) but may also affect stomatal conductance (affecting leaf water loss and evaporative cooling) and overall pasture water-use efficiencies. Corresponding increases required in fertiliser applications were adapted from the data specified by Quigley *et al*. (2003) (Table A3.2). One variant was considered:
   - increase the baseline fertility scalar by 0.10 units at each location.

The sustainable optimal stocking rate under SIGS conditions was re-estimated (using the methods described above) with each of the adaptation options in place. All results compare grazing systems at their sustainable optimal stocking rate.

Table A3.2. Data from Quigley *et al*. (2003) for mean annual pasture production at different fertiliser application rates, corresponding GrassGro fertility scalars and associated prices specified as annual pasture costs

Fertiliser applied (kg/ha/year)	GrassGro fertility scalar (-)	Pasture costs ($/ha/year)
11	0.43	6
45	0.47	23
90	0.62	45
130	0.78	65
170	0.84	85
260	0.86	130
375	0.86	188

<u>Results</u>

Effect of shorter growing seasons on gross margins

Long term average annual profit under historical weather conditions ranged from $520/ha at Hamilton to $102/ha at Wagga Wagga. Profits were primarily governed by allowable stocking rates, which were determined by the interaction of the minimum ground cover constraints, the climate and the soil fertility at each location (Figure A3.2).

Under a business-as-usual scenario, SIGS may decrease gross margins in most regions of southern Australia. However, it should be cautioned that the margin of variability associated with mean gross margins predicted under SIGS is well within the variability of current conditions (Figure A3.2), so effects of warmer, drier conditions forecast to occur by 2030 may not be significantly detrimental to southern grazing systems. At Hamilton, Goulburn, Wagga and Katanning, the variability of gross margins under SIGS was similar to historical conditions. In contrast, long-term variability declined at Cowra, Lucindale and Mt Barker suggesting that annual total income at these locations may become more uniform under future conditions.

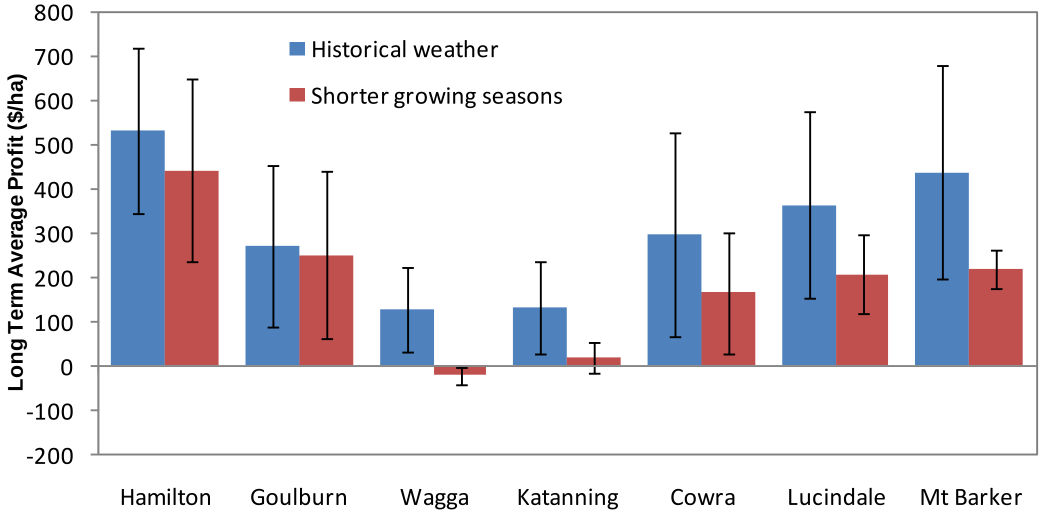

Figure A3.2. Long-term average annual profit modelled for Merino ewe enterprises producing first-cross lambs under historical (1970-1999) and shorter growing seasons at the seven locations. Error bars are ± one standard deviation.

Effects of shorter growing seasons on profit relative to historical baselines with alternative adaptation strategies

The effects of SIGS on long-term average profitability relative to historical baselines are shown in Table A3.3. Adaptation options shown in green in Table A3.3 indicate that the effects of shorter growing seasons may be mitigated by the intervention. Values in red imply that those changes to management would be detrimental to profitability under shorter growing seasons.

At Hamilton, several adaptation options were relatively capable of mitigating the effects of SIGS. Confinement feeding and sowing of early annuals were amongst the most advantageous (Table A3.3). Changing mating time to a month earlier (November cf. December) had a very small positive effect, while an older age at mating had a small negative effect. At the fertilizer prices and application rates assumed, increasing pasture fertility through increasing fertiliser application at Hamilton under future climates appeared to reduce gross margins slightly.

At Goulburn, beginning confinement feeding when total available dry matter fell to levels of 2000 or 1500 kg/ha was shown to be beneficial relative to the business-as-usual option (Table A3.3). In contrast to Hamilton, increasing pasture fertility may increase profitability at Goulburn under SIGS.

Table A3.3. Relative change in long-term average annual profit after undertaking each of a set of adaptation options under shorter growing seasons, relative to a 1970-1999 historical baseline with no adaptation, at seven locations across southern Australia. Cells shaded in green denote an improvement of 2% or more relative to no adaptation under shorter growing seasons (i.e. the values in the first row); cells shaded in red denote a decline in profit of 2% or more relative to no adaptation under shorter growing seasons.

The baseline scenario from which each adaptation option departs includes no confinement feeding; 1 Dec mating, first joining at 18 months; no additional annual grass in the sward; and standard fertility scalars (mostly corresponding to moderate soil fertility) at each location. Profit of each grazing system is compared at its sustainable optimum stocking rate, as defined in the text.

Adaptation option	Hamilton	Goulburn	Wagga Wagga	Katanning	Cowra	Lucindale	Mt Barker
No adaptation (except stocking rate)	-0.16	-0.08	-1.17	-0.85	-0.44	-0.43	-0.50
Confinement feeding, threshold to start 2000 kg DM/ha	-0.06	-0.01	-0.96	-0.98	-0.30	-0.45	-0.32
Confinement feeding, threshold to start 1500 kg DM/ha	0.00	+0.04	-1.02	-0.89	-0.39	-0.41	-0.42
Confinement feeding, threshold to start 500 kg DM/ha	-0.16	-0.09	-1.17	-1.02	-0.45	-0.43	-0.50
1 Nov mating, first joining at 6 months	-0.14	-0.09	-1.24	-0.91	-0.50	-0.53	-0.57
1 Nov mating, first joining at 18 months	-0.15	-0.08	-1.24	-0.91	-0.43	-0.53	-0.55
1 Nov mating, first joining at 30 months	-0.15	-0.09	-1.24	-0.91	-0.51	-0.53	-0.55
1 Dec mating, first joining at 6 months	-0.17	-0.08	-1.16	-0.85	-0.44	-0.43	-0.42
1 Dec mating, first joining at 30 months	-0.18	-0.06	-1.24	-0.93	-0.41	-0.52	-0.57
Early annual grass added to the pasture	-0.12	-0.06	-1.15	-0.84	-0.42	-0.46	-0.42
Very early annual grass added to the pasture	-0.14	-0.07	-1.35	-0.99	-0.42	-0.44	-0.46
Increased pasture fertility	-0.18	-0.02	-1.16	-1.05	-0.48	-0.46	-0.49

At Wagga Wagga and Katanning, shorter growing seasons sufficient to decrease NPP at Katanning by 10% were forecast to decrease average annual profit by 117% and 85% respectively. At Wagga Wagga, confinement feeding with a total available dry matter threshold of 2000 or 1500 kg/ha was the only adaptation option that moved profitability back toward historical levels to any extent, while at Katanning none of the trialled adaptation options was effective (Table A3.3). Results at Lucindale were generally similar to those at Wagga Wagga, except that the general level of profit decline under SIGS was smaller.

At Cowra, confinement feeding to higher dry matter thresholds somewhat reduced the effects of SIGS on gross margins. Shifting ewe joining times to a month earlier generally had negative effects on profitability due to the additional requirement for supplementary feed.

For Mount Barker, a number of adaptation options (including confinement feeding to higher dry matter thresholds, earlier joining and the addition of earlier-maturing annual grasses to the pasture) had some effect in reducing the impact of SIGS.

Generality of adaptation options across sites

Confinement feeding was the most generally applicable adaptation option; starting confinement at a threshold of 1500 kg/ha improved profit at 6 of the 7 locations. Using a threshold of 500 kg/ha, on the other hand, was an ineffective adaptation option; presumably by the time dry matter reached this level, a period of low ground cover was guaranteed by further DM decay.

Adding early (or very early) annual grass to the pasture improved profit by at least 2% of historical levels at 3 of the 7 locations (Hamilton, Cowra and Mount Barker); adding early annual grass had a smaller but positive effect at 3 further sites.

At the prices assumed, neither the mating time options nor increasing pasture fertility were effective adaptation options for dealing with shorter but more intense growing seasons.

Discussion and conclusions

Production of artificially shortened growing seasons

The method used to shorten growing seasons was implemented for the seven sites, and was capable of reducing total net primary productivity (NPP). However the approach of requiring a 10% reduction from baseline productivity at each location needs revision. Alternative approaches could be to uniformly contract the growing season (e.g. to define a set number of days to modify the breaks and ends of the season), or better, contract growing season length by a common proportion rather than total productivity. Nevertheless, the method developed in this study will be useful for further studies of shorter growing seasons of predicted conditions beyond 2030 since manipulation of historical records to a desired level is straightforward, rapid and conducive to iteration.

Which adaptation strategies will be most beneficial under future climates?

The diversity of climates across southern Australia mean that there is no universal change to management that will be potentially advantageous under future conditions. Table A3.3 indicates that multiple management adaptations could be advantageous at locations with relatively longer growing seasons, such as Hamilton, Goulburn and Mount Barker. Adaptation strategies at sites with relatively short duration seasons such as Lucindale and Katanning appear more limited. Indeed, no adaptation strategy tested at Katanning appeared to be better than outcomes projected to occur by adapting stocking rates only.

Most reductions in profit were a result of the necessity to reduce stocking rates to meet the minimum ground cover constraints. Incorporation of pasture species more resilient to removal by livestock may represent a strategy to overcome the minimal cover requirement and thus increase SRs. Strategies that allowed the greatest resting of pastures (e.g. confinement feeding with a high threshold) were generally most beneficial, since they allowed recovery of pasture growth and restoration of ground cover. Future investigation of strategies preserving or increasing ground cover would likely prove beneficial.

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Appendix 4. Will managing for climate variability also manage for climate change? A southern Australian grazing system as an example

Introduction

In writing about policy options for climate change adaptation in agriculture, Pannell (2010) has argued that farmers faced with a changing climate will successfully adapt their systems by means of successive small, short-term changes in management practice:

> "At any point in time, farmers will use those practices that suit current perceived conditions. Farmers would respond to change as it occurred, rather than responding to predicted changes. Even for adaptations that would take some years to implement, the pace of climate change is predicted to be easily slow enough for pre-emptive action to be unnecessary in many cases" (Pannell 2010).

Built into this argument, and therefore into the policy conclusions drawn from it, are two key propositions:

- *The feasible rate of on-farm practice change is faster than the rate at which changing climate will alter the production environment*. For cropping enterprises, this is self-evident since most decisions relating to a crop are taken in the year of production or the year before. Whether it holds for livestock production in southern Australia is not as clear, however, since livestock enterprises are inherently less agile. There are several reasons for this: the genetic base (both livestock and perennial pastures) represents a significant capital investment and so the transaction costs involved in changing genotypes are greater; changes in the age structure or a herd or flock will generally persist for 4-6 years; there are feedbacks between management and the vegetation (e.g. Cayley *et al.* 1999, Hill *et al.* 2004) that can affect future production; and the lags between decisions and production outcomes are longer – especially in cattle production – with the result that uncertainties at the point of decision are typically greater.
- *Farmers' perceptions of their current conditions will be sufficient to allow them to adjust their management strategies.* Here a rather different kind of question arises: what ways of arriving at a perception of "current conditions" – for example placing different weights on past experience and on projections of expected future conditions – might be most effective in adapting to a changing climate?

This study explores these two questions for a case study livestock enterprise by analysing four alternative policies for adapting two of the key profit drivers in grazing systems: stocking rate and the timing of the reproductive cycle. The four adaptation policies considered are:

- "Traditionalist" policy: maintain the optimal stocking rate and joining date from the 1970-2009 period.
- "Incremental" policy: make a small change in either stocking rate or joining date each year, based on relative profitability over the last 5 years. This policy is closest to the spirit of the approach to climate change adaptation described by Pannell (2010), in that it is both incremental (frequent, small adjustments) and backward-looking (the manager is guided by experience).
- "Step-change" policy: every 15 years, choose the stocking rate & joining time that optimized net profit over the previous 15 years. This policy is also backward-looking, but it differs from the incremental policy in consisting of infrequent, larger adjustments.

- "Forecast" policy: set stocking rate & joining time each year as functions of an accurate forecast of long-term expected pasture production. This policy is also incremental but is forward-looking, in that only the expected future is taken into account.

In previous studies of the impacts of, and adaptation to, climate change by livestock producers (Topp and Doyle 1996, Cullen *et al.* 2009, Alcock *et al.* 2010), climate at a single future date (e.g. 2030 or 2050) has been considered. This analysis is different, since it considers alternative ways of adapting a livestock production system to a climate that is undergoing continuous change over time, as done by Kirschbaum (1999) for forestry production.

When the climate at a single future date has been the focus, it has been possible to assess variability in the future climate by downscaling multiple years of weather from a single realization of a global circulation model (GCM). This is not possible when continuously-changing climates are the objects of study. Accordingly, in this analysis the uncertainties due to year-to-year and decade-to-decade variability have been taken into account by using multiple realizations of projected climate from each of two GCMs. Another new feature of this study is that the costs and prices in financial calculations are not left constant. Instead, each possible future climate is assigned its own set of varying prices and costs, so that the interaction between business and price risks is considered.

<u>Methods</u>

A dual-purpose sheep production system (Merino ewes producing first-cross lambs) was considered in this study. Sheep grazed annual grass-clover pastures at Lucindale, South Australia. Policies for setting stocking rates and joining dates were examined; overstocking was penalized via a requirement for confinement feeding in order to preserve ground cover.

Simulation models. The GRAZPLAN simulation models of the dynamics of grazed temperate grasslands (Freer *et al.* 1997; Moore *et al.* 1997) were used in this study. These models are widely employed within Australia for purposes of research (e.g. Clark *et al.* 2003; Mokany *et al.* 2010) and also in decision support for producers (Donnelly *et al.* 2002 and references therein; Warn *et al.* 2006). Owing to the complexity of the management system under consideration (in particular the need to vary stocking rates and joining dates over the course of a simulation), the AusFarm software (www.grazplan.csiro.au; Moore 2001) was used to carry out the simulations.

The behaviour of the GRAZPLAN models will respond to changes in climate and atmospheric CO_2 concentration in a variety of different ways. The GRAZPLAN pasture model accounts for four effects of increasing CO_2 concentration: reduced transpiration due to partial stomatal closure, a direct CO_2 fertilization effect, decreases in specific leaf area and decrease in leaf nitrogen content (Moore and Lilley 2010). Changes in rainfall at a location will mainly affect the dynamics of the models via the water balance. Effects of changes in soil water content on pasture growth rate and the decomposition of litter are represented in the pasture model. The key effects of increasing temperatures across southern Australia – at least for increases up to about 3°C – are also accounted for by model equations describing effects of increased temperatures on vapour pressure deficit, seed dormancy release, germination, plant phenology, rates of assimilation, respiration and decline in the digestibility of herbage (Moore *et al.* 1997), reductions in animal intakes on hot days, decreased energy expenditures by livestock in winter and lower peri-natal mortality of lambs (Freer *et al.* 1997).

Grazing system. A breeding flock of Merino ewes (breed standard reference weight 55 kg, reference greasy fleece weight 5.0 kg with 70% clean yield) was modelled. These ewes grazed annual pastures (a mixture of annual ryegrass, subterranean clover and capeweed). A set of 5 identical paddocks was available to be grazed; the duplex soil in each paddock was assumed to have a sandy loam topsoil and a clay subsoil with high bulk density (Table A4.1) that limited the rooting depth of all species to 400mm. As a result the plant-available water holding capacity of the soil was only 50 mm.

Table A4.1. Soil properties used in the simulations of a dual-purpose sheep production system at Lucindale

	Topsoil	Subsoil
Depth to base of horizon (mm)	300	800
Bulk density (Mg/m^3)	1.50	1.80
Wilting point (m^3/m^3)	0.08	0.15
Field capacity (m^3/m^3)	0.22	0.23
Saturated hydraulic conductivity (mm/hr)	100	1.0

Stocking rate and joining date varied between simulations and over time within some of the simulation runs. (In this analysis, “stocking rate” denotes the number of ewes per hectare in the flock – including weaner replacements and yearling ewes – immediately after old ewes are cast for age, and “joining date” refers to the start of a 42-day joining period rather than to the average date of conception.)

Ewes were first joined at 17 months of age. A proportion of the ewes was joined to rams of the same breed each year, so as to produce sufficient replacement ewes to maintain the current stocking rate. The youngest ewes in the breeding flock were selected for mating to Merino rams in order to minimize the risk of losses due to dystocia. The remaining ewes were joined to Dorset rams (breed standard reference weight 60 kg, reference greasy fleece weight 3.8 kg with 70% clean yield). Ewes that conceived in each oestrus cycle during joining period were simulated separately, as were their lambs. All male lambs were castrated shortly after the youngest lambs were born and weaning took place when the average age of lambs was 14 weeks. All weaner sheep not kept as replacement ewes were sold as soon as they reached a live weight of 50 kg, or else on 31 December.

All ewes and weaners were shorn on 25 November each year. Each 30 November, enough ewes were sold out of the oldest age cohorts in the flock to bring the size of the ewe flock back to the current stocking rate, i.e. stocking rate changes were implemented by varying the number of ewes that were culled from the flock. The age structure of the ewe flock therefore varied through time in simulations where the stocking rate was allowed to change.

Each week, animals were moved between the 5 paddocks so as to ensure that the best available forage was provided to crossbred weaners (if present), the next-best forage to Merino weaners, then successively to the maiden ewes, the weaners kept as replacements and the remainder of the ewes. In order to preserve the soil resource, any paddock with a ground cover less than 0.75 was closed to grazing. At times when all paddocks were closed to grazing, all stock were removed to a feedlot and fed wheat to maintain their current body condition. When sheep were in the pasture paddocks, the standard maintenance feeding rule used in the GrassGro decision support tool was used: if the body condition of a group of sheep at pasture fell below the thresholds shown in Table A4.2, then all sheep in that class of stock were fed (in their paddock) in order to prevent the body condition of the thinnest group from falling further.

Table A4.2. Condition score thresholds used to trigger maintenance feeding in the paddocks

Start of time period	Replacement ewe weaners	Other ewes	Other Weaners
Weaning	1.5	1.5	2.0
30 days before start of joining	2.0	2.0	2.0
Start of joining	1.5	1.5	2.0
Day 120 of average pregnancy	1.5	2.0	
Average lamb birth date	1.5	2.0	

Weather data and climate change projections. An historical daily weather dataset for Lucindale Post Office for the years 1961-2009 was obtained from the SILO database (Jeffrey *et al.* 2001, http://www.longpaddock.qld.gov.au/silo). These weather data were used in conjunction with monthly output from two global circulation models (GCMs) under the SRES A1B emissions scenario to generate time sequences of changing climate over the period 2010-2099.

Output from the CCSM3 (Collins et al. 2006) and ECHAM5/MPI-OM (Roeckner et al. 2003) models was used for this purpose. These two GCMs (and the A1B scenario) were selected because data from multiple runs were publically available; by evaluating each adaptation policy over an ensemble of GCM runs, the inherent uncertainty in the projected climates could be taken into account. Note well that the weather inputs used here differ in nature from those used in previous impacts and adaptation studies with the GRAZPLAN models (e.g. Alcock *et al.* 2010). In this study, each weather input file represents a climate that changes over time from 2010 to 2099; the previous studies have considered the year-to-year variability projected for specific future date (e.g. 2030).

Daily weather data sequences matching each projected climate (2 GCMs x 4 model runs per GCM) were constructed using a downscaling technique adapted from that of Zhang (2007). Briefly, the technique uses ranked monthly values from the historical weather record and outputs from a global circulation model to develop a locally-specific “transfer function” that maps the GCM-predicted monthly value to a location-specific monthly value. The resulting time sequences of monthly weather values are detrended when a weather sequence corresponding to the climate for a particular time is required, as in this study. Finally, a stochastic weather generator (Hansen and Mavromatis 2001) is used to convert the monthly time course of weather to daily values. Full details of the technique are given by Moore (2008). Atmospheric CO_2 concentrations were increased in the course of each simulation using a polynomial function fitted to the ISAM reference atmospheric CO_2 concentrations for the A1B emissions scenario (Houghton *et al.* 2001; Figure A4.1).

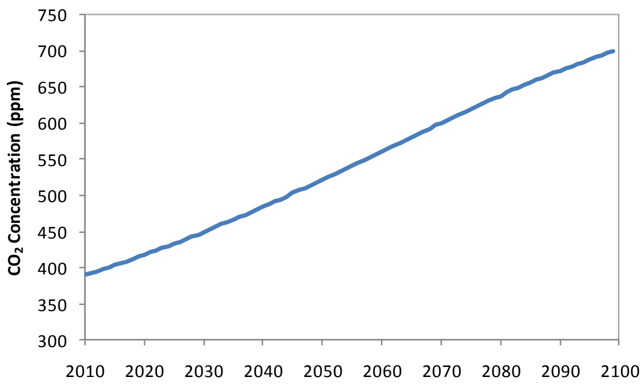


Figure A4.1. Atmospheric carbon dioxide concentrations for the A1B emissions scenario that were used in simulations of the Lucindale ewe production system under all projected climates.

Financial calculations. All financial calculations used a July-June year. The following production-related outputs were collected for each year of each simulation: numbers of ewes and lambs shorn and their average clean fleece weight, number of each class of lamb sold (male and female x crossbred and Merino) and their average weight at sale, number of ewes mated and total amount of supplement fed (in kg fresh weight). From this information, an annual profit (Y, \$/farm) was calculated as

$$
\begin{aligned}
Y = \; & \left(1 - VC_{sale,wool}\right) \cdot [\, F_{wool} \cdot P_{fleece} \cdot (NSH_{ewe} \cdot CFW_{ewe} + NSH_{mlamb} \cdot CFW_{mlamb}) \\
& \qquad + F_{wool} \cdot F_{xbred} \cdot P_{fleece} \cdot NSH_{xlamb} \cdot CFW_{xlamb} \,] \\
& + \left(1 - VC_{sale,stock}\right) \cdot [\, NS_{mlamb} \cdot (P_{lamb} \cdot F_{dress} \cdot LW_{mlamb} + P_{skin}) \\
& \qquad + NS_{xlamb} \cdot (P_{lamb} \cdot F_{dress} \cdot LW_{xlamb} + P_{skin}) \\
& \qquad + NS_{ewe} \cdot (P_{ewe} \cdot F_{dress} \cdot LW_{ewe}) \,] \\
& - C_{shear,ewe} \cdot NSH_{ewe} - C_{shear,lamb} \cdot (NSH_{mlamb} + NSH_{xlamb}) \\
& - FC_{sale,stock} \cdot (NS_{mlamb} + NS_{xlamb} + NS_{ewe}) \\
& - C_{husb,ewe} \cdot N_{ewe} - C_{husb,lamb} \cdot (NS_{mlamb} + NS_{xlamb}) \\
& - C_{ram} \cdot F_{ram} \cdot NM_{ewe} - C_{supp} \cdot SUPP - C_{pasture} \cdot AREA - C_{operator} \cdot AREA
\end{aligned}
$$

where NSH_{ewe}, NSH_{mlamb} and NSH_{xlamb} are the numbers of ewes, Merino lambs and crossbred lambs shorn; CFW_{ewe}, CFW_{mlamb} and CFW_{xlamb} are the clean fleece weights (kg/head) of these three classes of stock; NS_{ewe}, NS_{mlamb} and NS_{xlamb} are the numbers of each class of stock sold each year; LW_{ewe}, LW_{mlamb} and LW_{xlamb} (kg) are their average live weights at sale; N_{ewe} is the number of ewes present immediately after replacement; NM_{ewe} is the number of ewes mated; $SUPP$ (tonne) is the total amount of supplementary feed provided to livestock over the year; $AREA$ is the property area; P_{fleece} (\$/kg) is the price of clean fleece wool in the current year; P_{lamb} (\$/kg) is the carcass price for lambs in the current year; P_{ewe} (\$/kg) is the carcass price for mutton in the current year; C_{supp} (\$/tonne) is the price of supplementary feed in the current year; and the remaining constant prices and costs are set out in A4. 3.

The prices received for wool (average price over ewes and lambs, \$/kg clean fleece), lambs, (\$/kg dressed weight), cull sheep (\$/kg dressed weight) and supplementary feed (\$/kg fresh weight for wheat) varied from year to year. For simulations carried out over the historical record, historical price data from ABARES were deflated to Jun 2010 dollars; wool quality of purebred Merino sheep was assumed to result in the Eastern Market Indicator price. For each realization of each GCM, a synthetic sequence of these four prices was generated using the weakly stationary generating process of Matalas (1967). This generating process is also used in commonly-

Table A4.3. Constant costs, prices and multipliers used in the financial calculations for the Lucindale ewe enterprise.

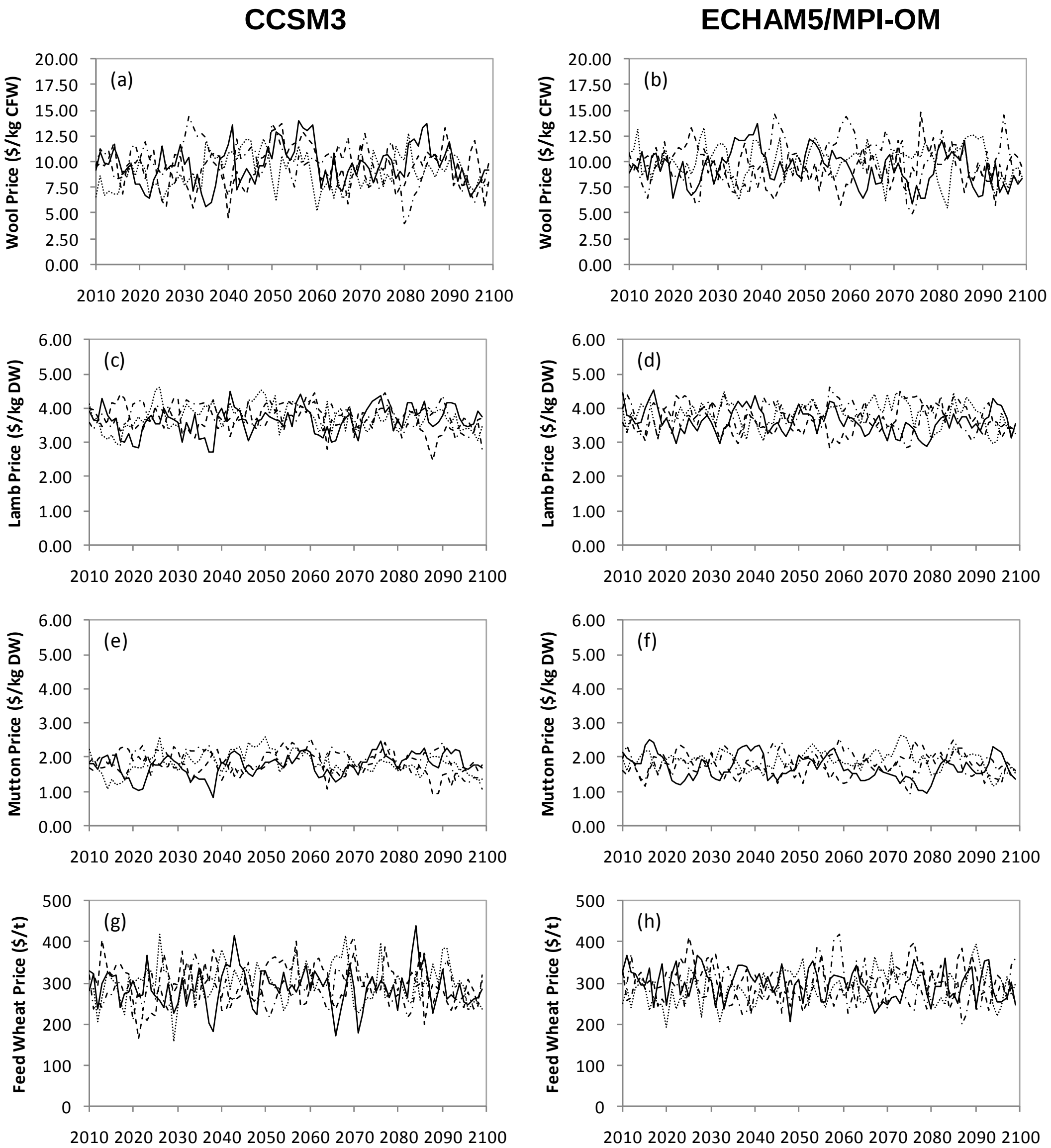
Variable	Meaning	Value	Unit
P_{skin}	Lamb skin price	5.00	\$/head
$C_{shear,ewe}$	Cost of shearing ewes	4.50	\$/head
$C_{shear,lamb}$	Cost of shearing lambs	4.00	\$/head
$VC_{sale,wool}$	Variable costs of wool sales (commissions etc)	0.04	\$/\$
$VC_{sale,stock}$	Variable costs of livestock sales	0.08	\$/\$
$FC_{sale,stock}$	Fixed costs of selling stock	2.00	\$/head
$C_{husb,ewe}$	Annual husbandry cost for ewes	3.80	\$/head
$C_{husb,lamb}$	Husbandry cost for lambs (birth to sale)	2.00	\$/head
C_{ram}	Purchase cost for rams	1000	\$/head
$C_{pasture}$	Cost of pasture management	35.00	\$/ha
$C_{operator}$	Operator labour allowance	100.00	\$/ha
F_{ram}	Rams purchased per ewe per year	0.04	–
F_{xbred}	Ratio of fleece price for crossbred lambs to fleece price for Merino rams	0.90	–
F_{wool}	Ratio of average wool price to fleece price	0.85	–
F_{dress}	Dressing proportion (carcass:live weight ratio)	0.41	–

Table A4.4. 2001-2009 average price levels (expressed in June 2010) dollars of key prices and costs, their coefficients of variation over 1983-2009 and correlations over 1983-2009. Values are calculated from Bureau of Agricultural Economics/Australian Bureau of Agricultural and Resource Economics data.

Commodity	Mean	C.V.	Correlation (r) with		
			Lamb	Mutton	Wheat
Merino wool (\$/kg clean fleece)	9.57	0.21	0.20	0.25	0.32
Lamb (\$/kg dressed weight)	3.69	0.11		0.86	0.14
Mutton (\$/kg dressed weight)	1.80	0.18			0.15
Feed wheat (\$/tonne)	291	0.15			

employed weather generators (e.g. Hansen & Mavromatis 2001). It produces a stochastic sequence of multiple variables which is stationary in time (i.e. the long-run expected mean does not change) and in which both the correlations between the variables and their lag-1 autocorrelations are preserved. Detrended ABARES price index values from 1982-3 to 2008-9 were used to derive the necessary correlation information and coefficients of variation, and the average real price of the four commodities over 2001-09 was used to set the expected long-run average price levels (Table A4.4). The resulting price sequences are shown in Figure A4.2.

Figure A4.2. Synthetic price sequences for 2010-2099, used in conjunction with four realizations of each the CCSM3 (a, c, e, g) and ECHAM5/MPI-OM (b, d, f, h) global circulation models.



Risk-weighted profit measure. A risk-averse manager was assumed. Risk aversion was taken into account by adding a weighted "conditional value-at-risk" to the average annual profit over a period of N years when ranking combinations of stocking rate and joining date, to obtain a "risk-adjusted profit", *Z* ($/ha):

$$Z = \frac{1}{AREA} \cdot \left(\frac{1}{N} \sum_{i=1}^{N} Y_i + \beta \cdot \frac{1}{\alpha \cdot N} \cdot \sum_{i: Y_i \leq Y_\alpha} Y_i \right)$$

The conditional value-at-risk at a nominated level α is the average of the profits obtained in the worst proportion α of years. The risk-adjusted average profit measure effectively gives extra weight to poor years when computing the average return over a period. Values of α=0.20 and β=0.50 have been used here, i.e. a 150% weighting to the 20% of years with lowest profits.

Simulation under historical climate. A simulation experiment was conducted in which the Lucindale ewe grazing system was simulated over the years 1970-2009 for all combinations of 5 joining times (15 Nov, 15 Dec, 15 Jan, 15 Feb, 15 Mar) and 12 stocking rates (from 4.5 to 10.0 ewes/ha at intervals of 0.5). The combination of stocking rate and joining time that gave the highest risk-adjusted average annual profit was then selected as the "historical optimum" management policy.

"Traditional" adaptation policy. The historical optimum management policy was simulated over Jan 2010 to Dec 2099 using downscaled weather data and stochastic prices for each of the eight projected climates.

"Incremental" adaptation policy. To analyse the incremental policy, a single simulation was run over the period Jan 2010 to Dec 2099 for each of the eight projected climates. Five separate farms were modelled within this simulation; these farms were identical in all respects except for their stocking rates and joining dates. The five modelled systems were a current-best stocking rate and joining date (i.e. the current result of the incremental policy), and four alternatives obtained by increasing stocking rate by 0.25 ewes/ha, decreasing stocking rate by 0.25 ewes/ha, making joining earlier by 3 days and making joining later by 3 days. (The motivation for this approach was that the results of different policies on neighbouring farms would be part of the information available to the manager adopting the incremental policy.) The historical optimum management policy was used as the current-best policy for 2010. Immediately prior to ewe replacement in each year from 2015 onward, the five alternative policies were ranked according to their average profits over the preceding five years (without risk adjustment) and the highest-ranking policy was adopted for the coming year. As a result either a small stocking rate change or a small joining date change could be made in each year, but not both at once. Because the set of stocking rate x joining time combinations being modelled changed each year, profits for the desired combinations in the four prior years were estimated from the combinations that were actually run by fitting and interpolating quadratic functions of profit vs stocking rate and profit vs joining date.

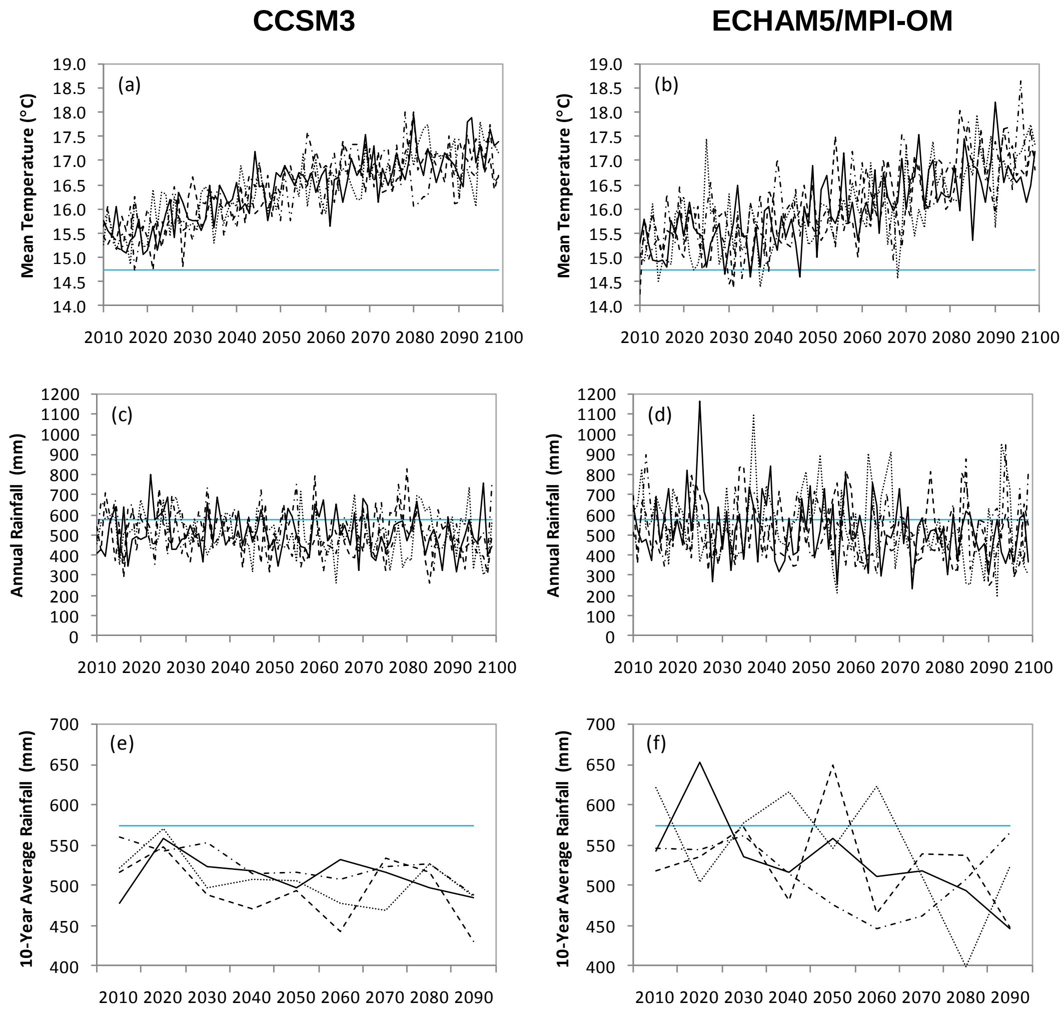
"Step change" adaptation policy. The step-change policy was analysed over the period Jan 2010 to Dec 2099 for each of the eight projected climates. Within each projected climate, the 90 years from 2010 to 2099 were divided into six 15-year periods and a single combination of stocking rate and joining date was selected for each period. For 2010-2024, the historical optimum management policy was selected. The management policy for the subsequent five periods was chosen as follows:

1. The previously-selected management policies for periods more than 15 years before the start of the period under consideration were simulated.
2. From the resulting common starting point (15 years before the start of the period), a simulation experiment was run with a range of combinations of joining time (in half-month intervals) and stocking rates (in steps of 0.5 ewes/ha). The exact set of policies examined varied from period to period to ensure that the policy with the highest risk-adjusted average profit for each climate and period was located.
3. The management policy highest risk-adjusted average profit for the previous 15 years was selected as the policy to be adopted *in the new 15-year period*. For example, the management policy for 2040-2054 was selected because it had the highest risk-adjusted average profit during 2025-2039.

Once the management policy for each of the six periods had been selected, a final simulation with the selected set of stocking rates and joining dates was run over the whole 90-year period.

"Forecast" adaptation policy. For this policy, a two-step procedure was followed. First, the annual above-ground net primary productivity (ANPP) of the pastures modelled for each year under the step-change adaptation policy was collated for each of the eight projected climates, and the average ANPP in each year over the four realizations was computed for each of the two GCMs. A quadratic regression was then fitted for each GCM, relating expected ANPP to year. Second, the optimal stocking rates, optimal joining dates and average pasture ANPP for each GCM x realization x 15-year period (i.e. 2 x 4 x 6 = 48 values) were collated. The optimal stocking rates and optimal joining dates were each regressed against ANPP. Linear regressions were found to be adequate. A single simulation was then run in which the expected ANPP for each year was calculated from the GCM-specific regression of ANPP versus year, and the expected optimal stocking rate was calculated from the common relationship between ANPP and stocking rate. Because there was no significant relationship between joining date and pasture ANPP, joining dates were left at the historical optimum value.

Figure A4.3. Annual mean temperatures, annual rainfalls and decadal average rainfalls of projected weather sequences at Lucindale that were downscaled from four realizations of the CCSM3 (a, c, e) and ECHAM5/MPI-OM (b, d, f) global circulation models over 2010-2099. Blue lines show the historical average value (over 1970-2009) for comparison.



Results

Projected climates. Annual mean temperatures and rainfalls under the eight projected climates are shown in Figure A4.3, along with decadal rainfall averages. Temperatures increase steadily between 2010 and 2099 for both GCMs under the assumed emissions scenario (SRES A1B), with increases for CCSM3 and ECHAM5/MPI-OM respectively of about 1.8°C and 1.2°C at 2055 and 2.3°C and 2.5°C at 2099 (i.e. CCSM3 exhibits faster warming than ECHAM5/MPI-OM in the first half of the period and slower warming in the second half). Average rainfall decreases by about 15% from historical levels by 2099 for both GCMs. Different realizations of the same GCM show large differences in decadal average rainfall, especially for ECHAM5/MPI-OM.

Figure A4.4. Modelled pasture production responses to a changing climate over 2010-2099 in a dual-purpose ewe production system at Lucindale, when the historical optimum stocking rates (7.5 ewes/ha) and joining date (15 Jan) are used. (a, b, c) Average monthly pasture growth rates under climate projected by the CCSM3 (◆) and ECHAM5/MPI-OM (◆) global circulation models for three 30-year successive periods, compared with the average modelled pasture growth rates for 1970-2009 (■). (d, e) Modelled trends in annual above-ground net primary productivity and the proportion of ANPP due to clover growth from 2010 to 2099 under climate projected by the CCSM3 (–) and ECHAM5/MPI-OM (–) global circulation models, compared with the 1970-2009 average (–). All projected values are averaged over 4 realizations of each GCM.

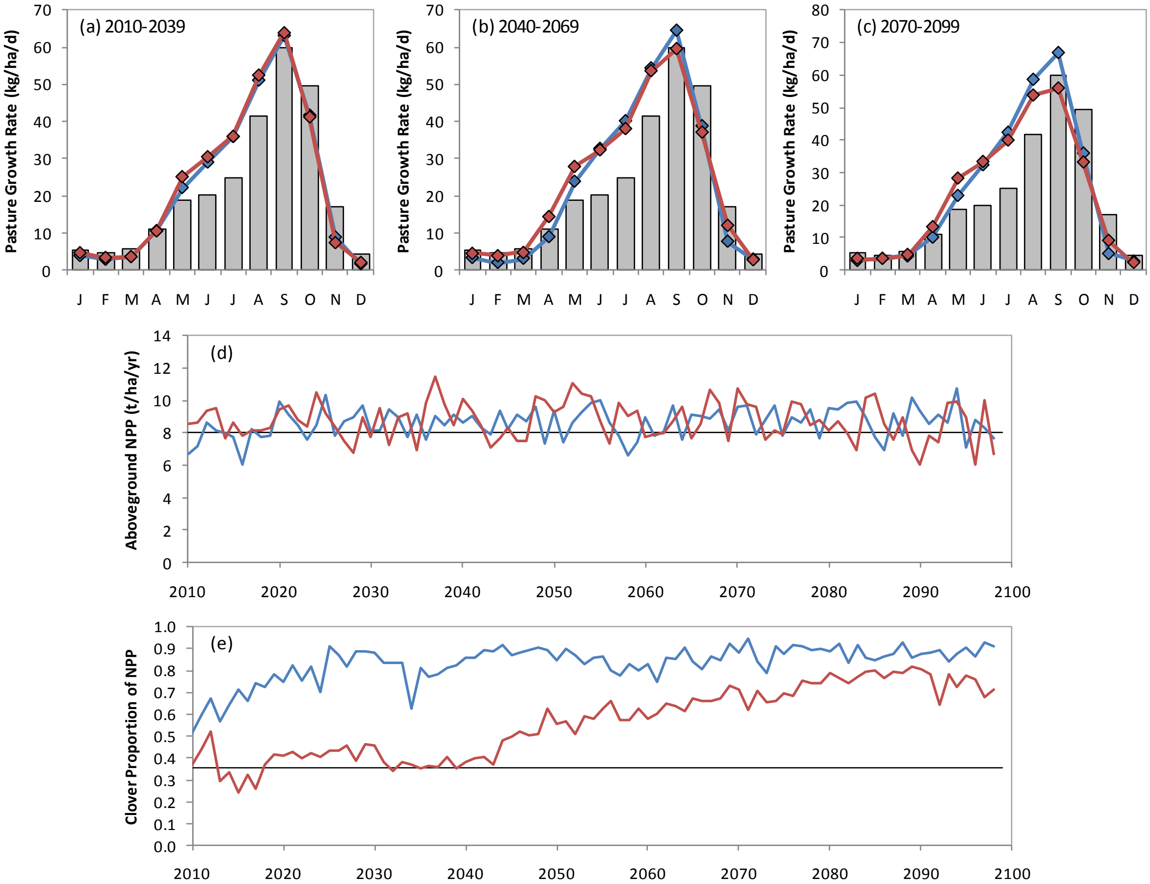
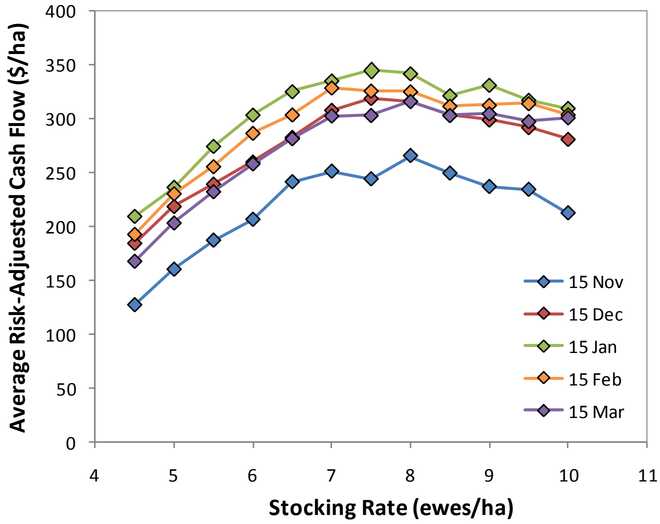


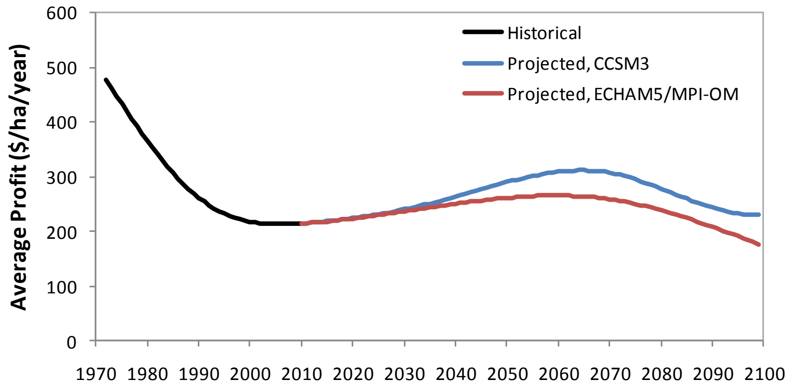
Figure A4.5. Response surface of risk-adjusted average profit of a dual-purpose ewe production system on annual pastures at Lucindale for 1970-2099 as stocking rate and joining date are varied.



Pasture growth under a changing climate. When compared with historical (1970-2009) results, the patterns of pasture growth under the projected climates show a pattern of higher winter growth rates and an earlier end to the growing season (Figure A4.4(a)-(c)). Unlike an earlier analysis at Canberra by Alcock *et al.* (2010), however, there is little if any delay in the start of pasture growth. Annual average pasture productivity increases by about 9% from 2010 to 2099 under the CCSM3-projected climate but shows no change under the ECHAM5/MPI-OM-projected climate (Figure A4.4(d)), despite the lower average rainfall projected for late in the centrury. The GRAZPLAN models predict a major shift in pasture composition, with a move to clover dominance over time.

Historical optimum management policy. The combination of 7.5 ewes/ha and a joining date of 15 January gave the highest risk-adjusted profit over 1970-2009 of all management policies examined. A typical “flat-topped” profit response was observed, however, with near-optimal values obtained over a range of stocking rates and also for a 15 February joining. Spring (15 November) joining was clearly sub-optimal. Average rates of profit declined sharply over the historical period (Figure A4.6), as a result of declining real prices for wool.

Figure A4.6. Time course of average annual profit for the Lucindale dual-purpose ewe production system at a fixed stocking rate of 7.5 ewes/ha and a joining date of 15 January. Curves have been fitted to the individual profit values computed from model results (all GCM realizations combined, see Figures 7 and 8) using natural cubic splines with fixed knots at 1990, 2010, 2040 and 2070.



"Traditional" adaptation policy. Annual profit values for the traditional management policy under each of the eight realizations of projected climate are shown in Figures A4.7 and A4.8, and smoothed time courses of average profit are given in Figure A4.6. Despite the projected decreases in rainfall, average profitability of the grazing system rises slowly through to mid-century for both GCMs and then decreases again. The temporary rise in system profitability is greater for the CCSM3 projection than the ECHAM5/MPI-OM projection, which is consistent with its higher average pasture productivity and earlier shift to legume-dominance. For both GCMs, the traditional adaptation policy resulted in a higher risk-adjusted average profit than did the historical simulation over 1990-2010. Overall, however, it seems likely that climate change adaptation for this grazing system at this location will be more a matter of capturing opportunities than of responding to deteriorating conditions.

Figure A4.7. Changes in stocking rate and joining date and the resulting annual grazing system profits of a dual-purpose ewe production system at Lucindale under changing climate projected by the CCSM3 global circulation model from 2010 to 2099. Each row of the figure shows results for one of four policies for adapting stocking rate and joining date, as described in the text. Each coloured line denotes outcomes for a weather sequence downscaled from a realization of the CCSM3 global circulation model under the SRES A1B emissions scenario. 1990-2010 average values for the historical optimum grazing system are shown as grey lines.

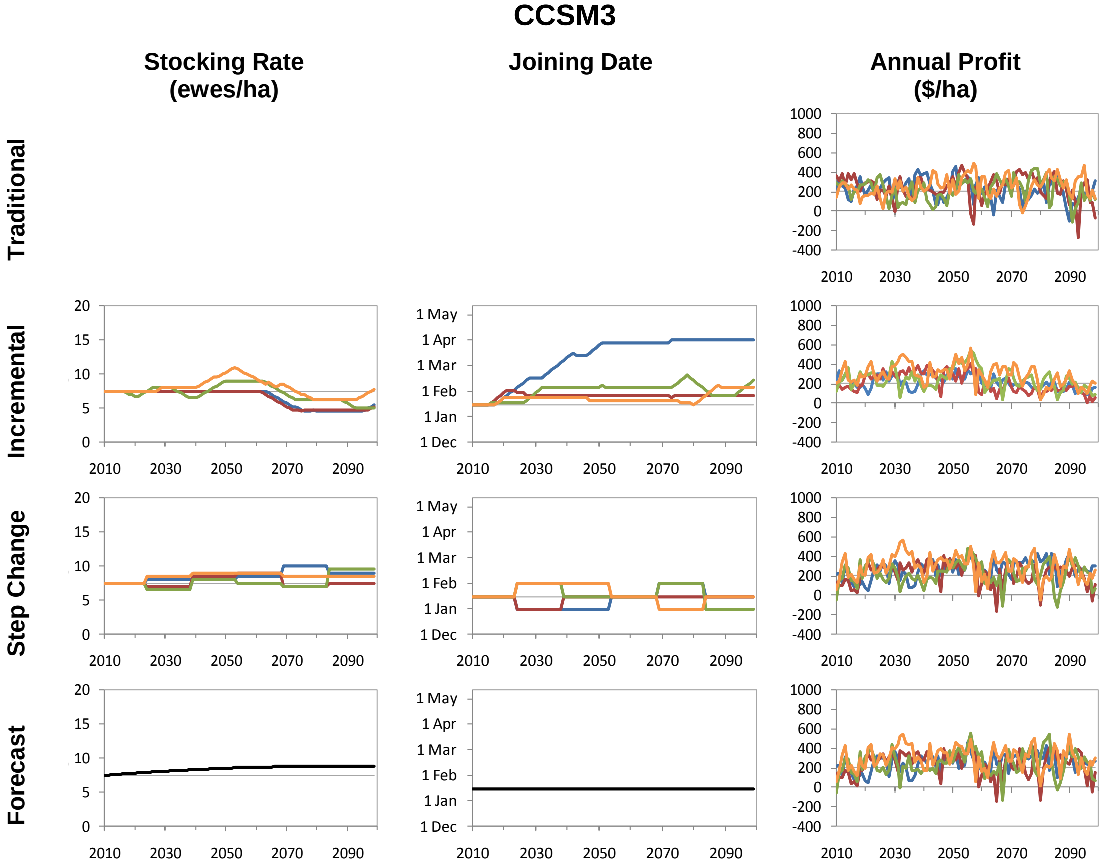
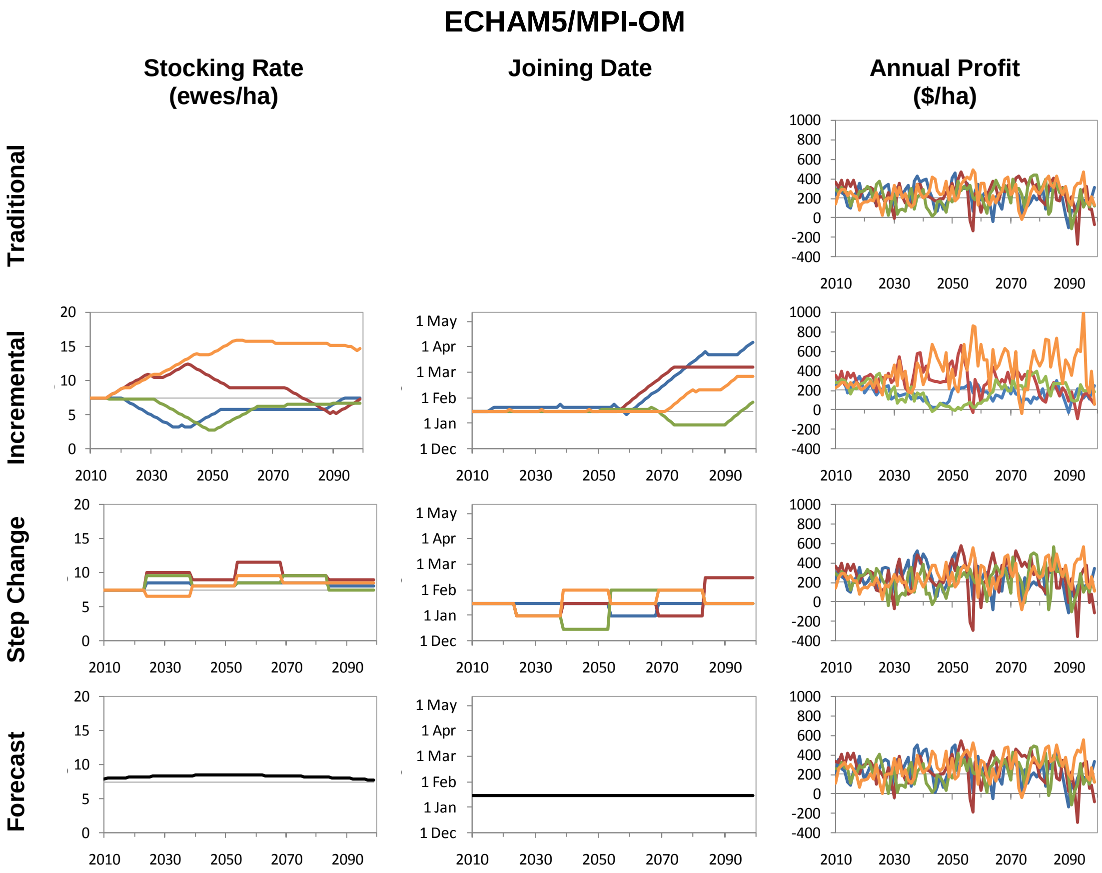


Figure A4.8. Changes in stocking rate and joining date and the resulting annual grazing system profits of a dual-purpose ewe production system at Lucindale under changing climate projected by the ECHAM5/MPI-OM global circulation model from 2010 to 2099. Presentation is as for Figure A4.7.



"Incremental" adaptation policy. Management policies (i.e. combinations of stocking rate and joining date) resulting from the incremental adaptation policy proved to be very different both between projected climates (CCSM3 vs ECHAM5/MPI-OM) and between realizations of the same climate. For the CCSM3 projection, stocking rates remained close to the historical-optimum level until about 2040, rose in two of the four realizations and then fell in all four realizations between about 2060 and 2080. By 2099 the selected stocking rate was in the range 5.0-5.5 ewes/ha for three of the four realizations. Meanwhile the joining dates selected in this realization moved later than the 15 January starting point; in one realization the joining date moved as far as early April (i.e. an early September lambing).

Under the ECHAM5/MPI-OM projected climate, joining dates shifted very little until about 2055; the different realizations then followed individual (but generally later) trajectories. The selected stocking rate trajectories were very different between realizations. In one realization, stocking rate built up to 16 ewes/ha in 2060 before declining slightly. At these stocking rates, significant supplementary feeding (20-80 kg wheat/ewe/year) is required every year to maintain the sheep flock over summer.

As can be seen in Figure A4.8, the end-points of the grazing systems under the four realizations of ECHAM5/MPI-OM were each quite different. One system had a high stocking rate, a high average profit and high year-to-year profit variability, and there were joining dates in January, February, March and April. Over the 90-year period, the incremental adaptation policy resulted in a higher risk-adjusted average profit than the 1990-2010 base period for two of the ECHAM5/MPI-OM realizations and a lower risk-adjusted profit for the other two.

"Step-change" adaptation policy. Basing infrequent management changes on the last 15 years' outcomes resulted in smaller, and more consistent, changes than the incremental adaptation policy (Figures A4.7 and A4.8). Late-lambing systems were not selected by the step-change policy – the latest lambing date chosen was 15 February – and stocking rates only moved within the range 6.5-11.5 ewes/ha (cf 2.8-16.0 ewes/ha for the incremental policy). There was something of a tendency for stocking rates to increase and then decrease over 2010-2099 for both GCMs.

"Forecast" adaptation policy. The forecasts for aboveground net primary productivity (*ANPP*, kg/ha) were estimated as:

$ANPP = 7674 + 48.7 \times (year - 2009) - 0.329 \times (year - 2009)^2$ CCSM3
$ANPP = 8346 + 32.6 \times (year - 2009) - 0.401 \times (year - 2009)^2$ ECHAM5/MPI-OM

No relationship between *ANPP* and optimal joining date could be detected, so for this policy all joining dates were left at 15 January. The relationship between stocking rate (SR, ewes/ha) and *ANPP* was estimated over both GCMs to be:

$SR = 1.71 + 0.00075 \times ANPP$

The resulting management policies for the two GCM-projected climates were not very different from the "historical optimum" policy. For CCSM3, stocking rate started at 7.5 ewes/ha, increased to 8.8 ewes/ha in 2083 and then declined very slightly. The selected stocking rate for ECHAM5/MPI-OM started at 8.0 ewes/ha, increased to 8.5 ewes/ha by 2050 and then declined to 7.8 ewes/ha by 2099. Profit levels over 2010-2099 showed a similar trajectory but overall were slightly higher than for the traditional adaptation policy.

Table A4.5 compares the profitability outcomes of the four adaptation policies (measured as risk-adjusted profit over 2010-99) with a 1990-2010 baseline and with one another. On average, all four adaptation policies – including no change – produce risk-adjusted profit levels that are higher than 1990-2010 under changing climate and stationary, but varying, prices. One likely reason for this was the use of a confinement feeding policy in poor summers in the modelled grazing system; this tactic appears to have been cost-effective as a means of maintaining stocking rates (and hence average profitability) at or above historically optimum levels.

Discussion and conclusions

In this case study, Pannell's (2010) contention that on-farm practice change can keep pace with a changing climate is clearly borne out. If it comes to pass, the shift to legume dominance predicted by the GRAZPLAN models will be clearly apparent to graziers, but the long-term shifts in profitability over time shown in Figure A4.6 are quite small relative to the year-to-year variability that is apparent in Figures A4.7 and A4.8 and his argument that changes in profitability will be hard to discern amongst year-to-year "noise" is also supported.

For the incremental policy and the ECHAM5/MPI-OM projected climate, major differences between climate realizations appeared. In two realizations this adaptation policy was much more profitable than the historical baseline, while for the other two – where short-term conditions led to transient drops in stocking rate – it was much less profitable. It appears that intra-decadal variation around the same mean climate and prices can entrain very different trajectories from incremental management. Indeed,

Table A4.5. Differences in risk-adjusted average annual profit ($/ha) between each realization of two projected climates and the historical optimum policy for over 1990-2010, the frequency with which each adaptation policy had the highest risk-adjusted profit for a given climate realization ("best policy") and the frequency with which the incremental, step change and forecast policies had higher risk-adjusted profit over 2010-2099 than the traditional adaptation policy ("better than traditional").

	Traditional	Incremental	Step Change	Forecast
CCSM3	+50	+32	+79	+64
	+78	+5	+3	+18
	+34	+55	+3	+35
	+78	+120	+106	+127
Average	+60	+53	+48	+61
S.D. Over Realizations	21	48	53	48
ECHAM5/MPI-OM	+12	-43	+27	+20
	+25	+92	+5	+25
	0	-44	-16	+6
	+62	+254	+56	+77
Average	+25	+65	+18	+32
S.D. Over Realizations	27	141	31	31
Best Policy?	1/8	3/8	2/8	2/8
Better than Traditional?		4/8	3/8	7/8

the high-stocking-rate system arising in one of the realizations can be regarded as a transformational change in management that has emerged from incremental adaptation.

None of the four adaptation policies consistently outranked all others in terms of risk-adjusted profit (Table A4.5). The forecast policy did better than the traditional policy in 7 of the 8 climate+price realizations, and so can be regarded as a robust alternative to no change, but it usually only improved economic performance by a modest amount (Table A4.5). The incremental policy did better – often much better – than traditional management in 4 of the 8 realizations but was not resilient to uncertainty in future climate. The step-change policy did not appear to offer any advantages over unchanged, stable management. One possibility worth exploring further is that a combination the forecast and incremental policies may retain the attractive features of both.

A final point is that the profitability results obtained under different realizations of the same GCM were fairly variable even under constant management. This suggests that multiple simulations, based on ensembles of GCM results, should be carried out routinely when using biophysical simulation models to examine climate change impacts and adaptation, especially under changing climates as in this study. Ensembles of GCM realizations are available for relatively few GCMs at present, however, and so this will probably have to wait until the results of the fifth Climate Model Intercomparison Project (CMIP5) are generally available.

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Appendix 5. Medium-term climatic variability and its effects on pasture and livestock production

Introduction

At the commencement of this project in 2009, southern Australia had just emerged from the “Millennium Drought” – an extended period of dry conditions in Southern Australia. It was clear at the time that this drought had significantly affected the productivity and livelihoods of livestock producers. It was not clear, however, whether this long drought was a consequence of “normal” medium-term climatic variation or whether it was a unique event.

Modelling pasture and livestock production under climate variability can give insights into the probable effects of rainfall variation and uncertainty. Previous modelling studies that have examined these issues across large areas have used ecohydrology models (Eagleson 2002; Kochendorfer et al. 2010) and have focussed on vegetation cover and runoff production. The consequences of medium-term rainfall changes on pasture livestock production have been examined at small numbers of sites in south-eastern Australia (Salmon et al. 2007; Cullen et al. 2011), but a large-scale examination of the effects of medium-term rainfall variability on livestock production has not yet been attempted.

In this analysis, a simulation experiment based on the GRAZPLAN biophysical models is used to explore the effects of medium-term climatic variations in the historical record on pasture and livestock production, while holding the management of grazing systems (plant and animal genetics, soil fertility etc) and their financial environment constant. Our aims are to clarify the uncertainty of pasture and livestock production under the spatially and temporally varying climates of southern Australia, and in particular to place recent climatic conditions in their longer-term context.

Methods

The GRAZPLAN grassland simulation models (Moore et al. 1997, Freer et al.1997; www.csiro.au/grazplan), as implemented in the GrassGro decision support tool (Moore et al. 1997), were applied in order to simulate the potential effects of medium-term climate variation between 1899 and 2010 on pasture and livestock production. The historical period was divided up into 8 periods, each 14 years in length. Each period is denoted by its midpoint, i.e. 1906, 1920, 1934, 1948, 1962, 1976, 1990 and 2004.

The models simulated pasture and livestock dynamics under historical climate data at a set of 25 locations chosen to be representative of southern Australia. At each location, five grazing enterprises (self-replacing Merino ewes, crossbred ewes, self-replacing Angus beef cattle, Angus steers and Merino wethers) were modelled. More detail on the development of the set of modelled grazing systems can be found in Appendices 7 and 11.

The set of simulations was designed to keep as many factors as possible constant, so that modelling results could be used to compare the effects of climatic variation over time and space. Atmospheric CO_2 concentrations of 350 ppm and present-day pastures and livestock were modelled at all time periods. Management policies (livestock replacement, the timing of the reproductive cycle, the sale of young stock and thresholds for supplementary feeding) were not changed from 1899 to 2010, with the exception of stocking rates. For each time period x location x enterprise combination, an “optimal sustainable” stocking rate was selected that maximized profit within a constraint that the frequency of low ground cover should not exceed a

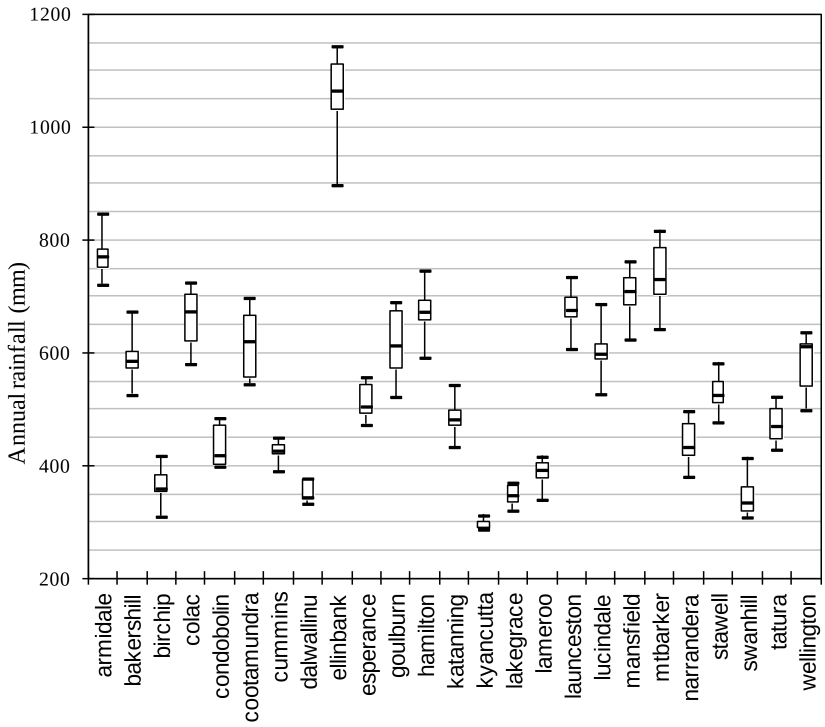


Figure A5.1. Variation of 14-year average rainfall across 25 representative locations in southern Australia. Boxplots illustrate the median (thick line), 10th, 25th, 75th and 90th percentiles. Each boxplot shows the distribution of average annual rainfall over a set of eight 14-year periods, starting with 1899-1912.

location-specific threshold. Within each enterprise, the same livestock genotypes, recent prices for livestock and wool and recent variable costs of production were assumed.

A three-way factorial simulation experiment was conducted in which the factors were time period within the historical record (8), location (25) and livestock enterprise (5). For each combination, a range of stocking rates was modelled. Physical and financial outputs from the grazing system were stored from each simulation run. A long-term rate of operating profit was calculated as the gross margin less overhead costs, an operator allowance and a further adjustment for the capital cost of the livestock required. An optimal sustainable stocking rate was selected as that which gave highest profit while keeping the frequency of low ground cover of at least 70% below a location specific threshold; all results are reported at this stocking rate.

Results

Rainfall

Long-term (1899-2010) annual average rainfall ranged from a minimum of 297 mm at Kyancutta to a maximum value of 1058 mm at Ellinbank. As shown in Figure A5.1, Ellinbank had the largest variation among locations (S.D. = 76 mm) while Lake Grace had the lowest variation (S.D. = 18 mm). The expected relationship of increasing rainfall variability with increasing average rainfall across locations was clearly evident (Figure A5.2).

Averaged over the locations, 1997-2010 was the driest of the eight 14-year time intervals across southern Australia with an (area-weighted) average annual rainfall of 479 mm; the wettest period was 1955-68, where the corresponding average rainfall was 560 mm. Average rainfall was least variable across locations in 1997-2010

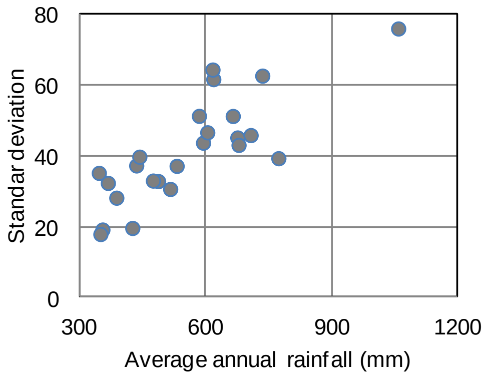


Figure A5.2. Relationship between standard deviation and average of annual rainfall of the eight focus periods. Each point denotes a location.

(area-weighted S.D. = 134 mm), showing that this dry period affected entire southern part of Australia. The largest variability across locations was observed during 1941-54 (S.D = 175 mm), which was the second-wettest of the 8 time periods.

Temperature

Annual average temperatures are less variable over time than annual rainfall. As shown in Figure 3, average temperature was least variable at Stawell (S.D = 0.15ºC) and the most variable at Colac (S.D = 0.55 ºC). Over the examined locations, there was no correlation between the standard deviation and annual mean values of temperature.

Above-ground net primary productivity (ANPP)

Long-term average area-weighted ANPP across Southern Australia was modelled to

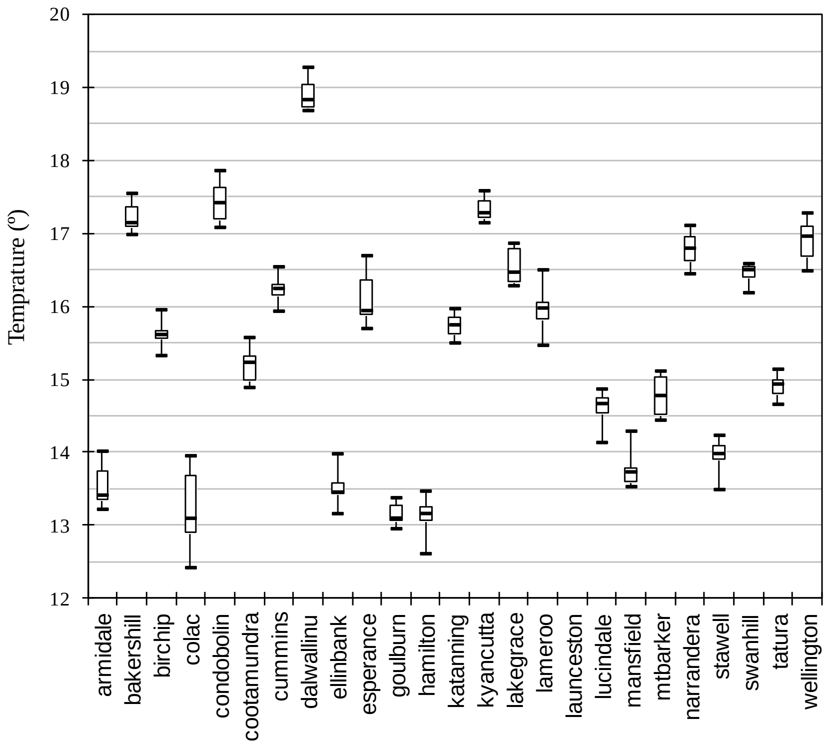


Figure A5.3. Boxplots showing the variation of 14-year average temperatures across 25 representative locations in southern Australia. Each boxplot shows the distribution of average mean temperature over a set of eight 14-year periods starting with 1899-1912.

Figure A5.4. Area-averaged annual aboveground net primary productivity across 25 regions of southern Australia in each of eight 14-year periods when modelled with present-day grazing systems.

be 6.2 t/ha. Over the 1899-2010 period, the average ANPP estimated for the single Tasmanian location (Launceston) was 8.5 t/ha. South Australia had the lowest state average ANPP of 5.2 kg/ha, with locations ranging from 3.1 t/ha to 8.4 t/ha. For Victoria, pasture production was estimated to range from 3.5 t/ha to 14.0 t/ha with an average 7.6 t/ha. New South Wales had average value of 5.6 t/ha (3.4 to 8.1 t/ha across locations), and for Western Australia the average was 5.7 t/ha (2.9 to 11.3 t/ha across locations).

Over the eight 14-year time periods, there were five periods with very similar area-weighted average ANPP and three periods (1899-1912, 1927-1940 and 1997-2010) where it was much lower (Figure A5.4). Pasture production across South Australia over the 1997-2010 period was estimated to be 22% lower than the 1899-1996 average; the corresponding decline in Tasmania was estimated to be only 3%.

The modelled variability of annual ANPP also differed between locations (Figure A5.5). Bakers Hill had the lowest ANPP variability with a standard variation of 0.22

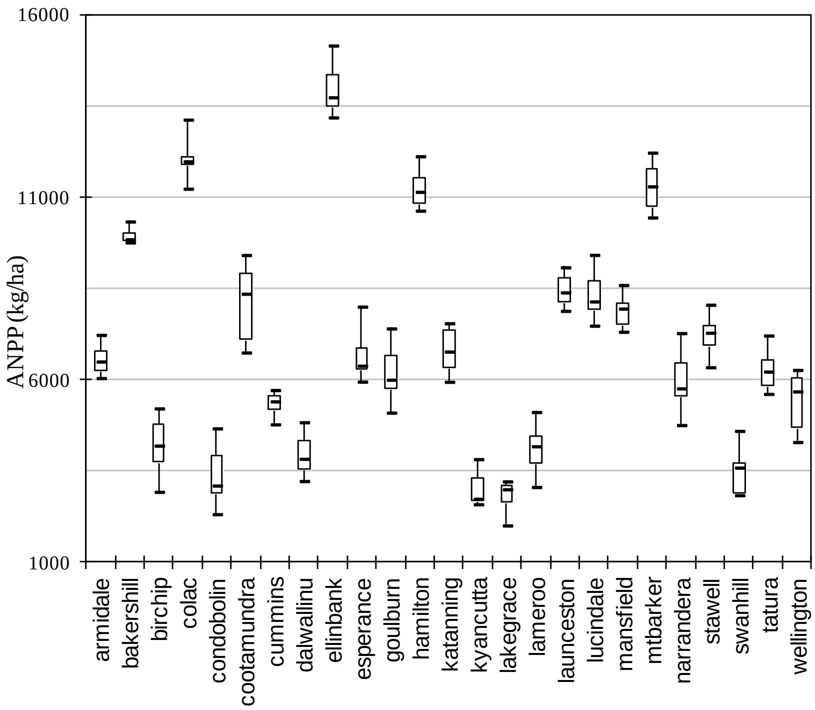


Figure A5.5. Boxplots showing the variation of 14-year average aboveground net primary productivity across 25 representative locations in southern Australia. Each boxplot shows the distribution of average annual ANPP over a set of eight 14-year periods starting with 1899-1912.

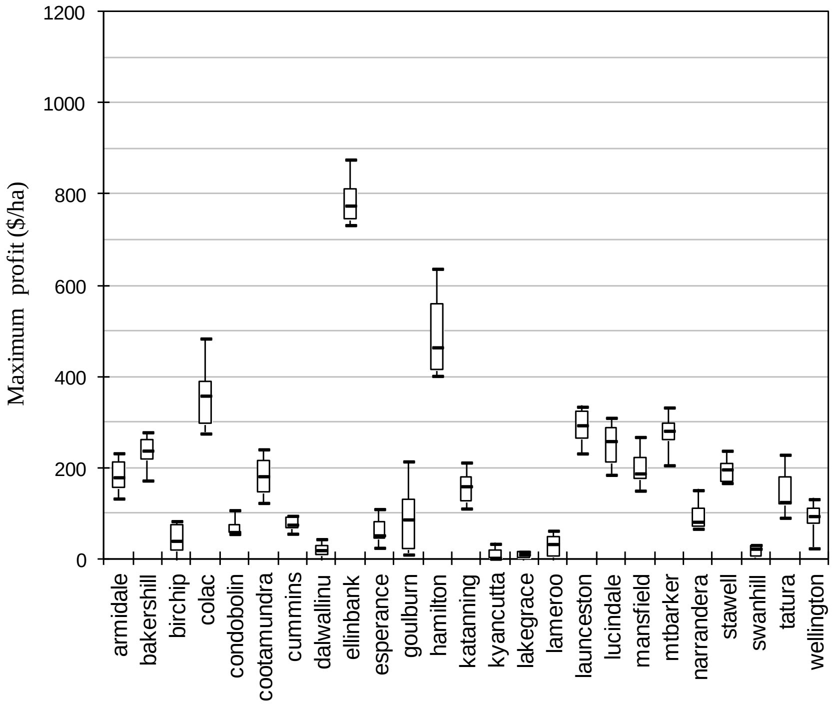


Figure A5.6. Boxplots showing the variation of 14-year average operating profit across 25 representative locations in southern Australia. Each boxplot shows the distribution of average annual operating profit (at the period's optimal sustainable stocking rate) over a set of eight 14-year periods starting with 1899-1912.

t/ha; Cootamundra and Narrandera had most variable of pasture production, with standard deviations of 1.03 and 0.83 t/ha, respectively. As expected, mean ANPP was lower at locations with lower rainfall. No relationship was observed between modelled ANPP and its standard deviation across either locations or focus periods.

Operating profit

The highest modelled long-term average operating profit (at the optimal sustainable stocking rate) was found at Ellinbank (Victoria) with $910 /ha/year, and the lowest estimated operating profit was at Lake Grace ($1/ha/year). The highest variation and consequently uncertainty of maximum profit among the locations were at Colac, Goulburn and Hamilton; however the lowest profit values at Colac and Hamilton were still larger than the maximum at most of the other locations (Figure A5.5).

When comparing States, South Australia had the lowest average profit at optimal sustainable stocking rates ($93/ha, with locations ranging from $13/ha to $253/ha. The mean operating profit of Victorian locations was $279/ha (range $18/ha to $785). For New South Wales the corresponding figure was $124/ha (range $69 to $183/ha); in Western Australia it was $126/ha ($9 to $275/ha); and for the single Tasmanian location, operating profit was 291 $/ha.

Variability and uncertainty of production at national, state and regional scales under variable climate

Taken across southern Australia, operating profit over the 8 time periods was non-linearly related to the both annual rainfall and the standard deviation of annual rainfall for the period, with declining returns to increasing annual rainfall (Figure A5.7). As shown in Figure A5.7, period-average operating profit was more closely related to the standard deviation of rainfall than to average rainfall. Variability of operating profit variation was not related either to rainfall or to its spatial variability.

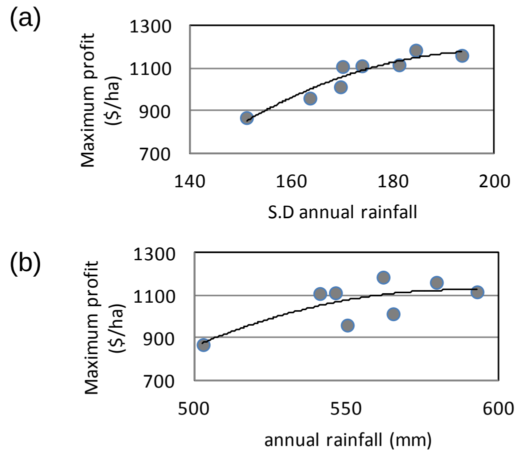


Figure A5.7. (a) Relationship between standard deviation of maximum profit over classified time periods and annual rainfall depth and (b) standard deviation of rainfall.

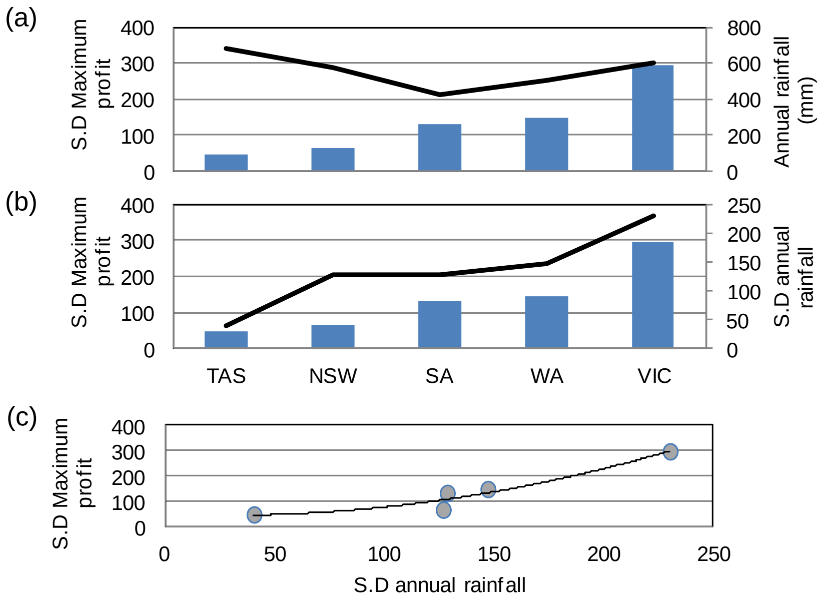


Figure A5.8. Trend of change in standard deviation of maximum profit at states (column) with (a) annual rainfall shown with solid line and (b) standard deviation of annual rainfall. (c) Relationship between standard deviations of maximum profit and annual rainfall as index of variability

As shown in Figure A5.8(a), the standard deviation of operating profit and annual rainfall didn't have similar trend, but had similar trend with standard deviation of rainfall (Figure A5.8(b)), and there was a slightly non-linear relationship between standard deviations of maximum profit and standard deviation of annual rainfall depth (figure A5.8(c)). However individual examination of locations didn't demonstrate similar trend of maximum profit was observed in association to either annual rainfall or standard deviation of rainfall (Figure A5.9).

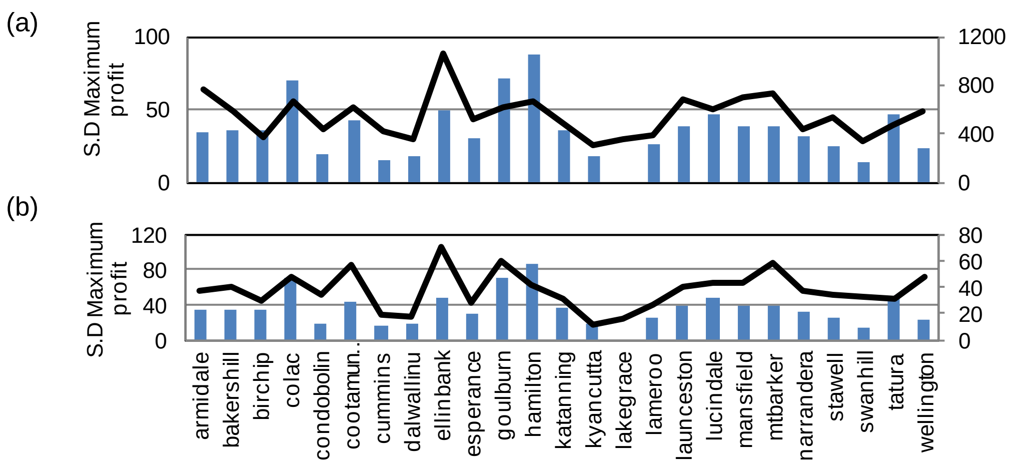


Figure A5.9. Standard deviation of operating profit over 1899-2010 at each of 25 locations (columns, left axis) compared with (a) mean annual rainfall (solid line, right axis) and (b) standard deviation of annual rainfall.

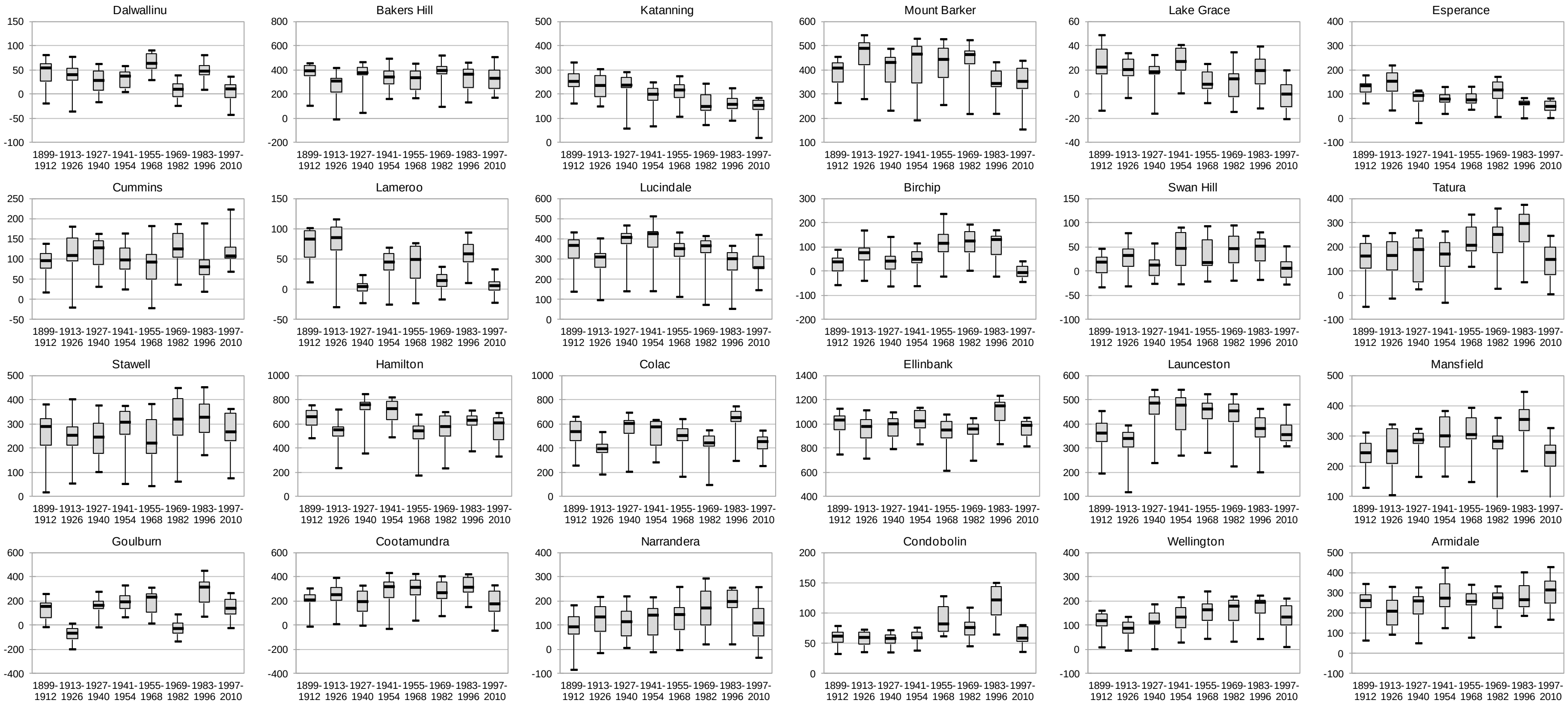
The null hypothesis that the rainfall, temperature, ANPP, and maximum profits at focus dates of 1906, 1920, 1934, 1948, 1962, 1976, 1990 and 2004 followed a normal distribution was rejected by a t-test at all locations. The only exception was normality of operating profit distribution at Birchip.

Operating profit and its variability at local scales

Figure A5.10 shows modelled average operating profit and its variability (at individual optimal sustainable stocking rates) at each location over each of eight 14-year periods going back to 1899. Examination of these figures shows that the locations fell into a relatively small number of groups:

- At most of the Western Australian locations, profitability during 1997-2010 was lower than in the other 7 periods but this reflected a steady decline in the climatically-driven level of profitability, rather than a sudden shift. (Bakers Hill was an exception, showing no clear trend over time.) Lameroo (SA) exhibited a similar, but less pronounced, pattern.
- At Cummins (SA), no trends in profitability over time could be discerned; profitability in the 1997-2010 period fell within the range found in other periods.
- The six Victorian sites, Launceston (Tas), Lucindale (SA) and Cootamundra (NSW) showed increasing profitability early in the long-term record followed by later decreases. At Hamilton, Colac, Stawell and Launceston the 1997-2010 period, while less profitable than the immediately preceding period, fell within the overall range of climatic conditions as a driver of livestock systems; at the other 5 locations the 1997-2010 period showed a lower average operating profit than all of the 7 preceding periods.
- At Armidale, there was a generally increasing trend in profitability that continued into the 1997-2010 period.
- The other 3 New South Wales sites (Narrandera, Condobolin and Wellington) also exhibited a long-term trend of increasing profitability. At these locations the 1997-2010 period was much less profitable than the immediately preceding period, but there were earlier periods that were less profitable.

Figure A5.10. Boxplots showing modelled annual operating profit of a Merino ewe enterprise over 8 periods from 1899 to 2010 at each of 25 locations across southern Australia. Locations are arranged geographically, and the scales for each location are different so as to show the differences between periods more clearly.



There was no evidence to suggest an increase in the variability of profitability (measured in absolute terms) at any of the locations, either comparing the 1997-2010 period with the rest of the historical record or as a trend over time.

Discussion and Conclusions

As expected, there was a strong relationship between the variability of rainfall over the medium term (14-year periods) and average rainfall at a location (Figure A5.2); locations with high rainfall and larger variability still had higher minimum rainfalls than locations with low rainfall. Annual rainfall variability differed among locations across Southern Australia in ways that that may lead to different risk profiles among locations as climate changes.

Modelled ANPP showed much lower variation than did operating profit, demonstrating higher degree of uncertainty in profit modelling. This increased uncertainty can be result of uncertainties in model input, model structure, current animal modelling formulations, and also averaging five probable livestock systems without selecting the most suitable one.

The modelled variability of operating profit between periods looked quite different at different spatial scales. Over southern Australia as a whole or across States, operating profit or its medium-term variability could be related to the medium-term variability of rainfall (Figures A5.7 and A5.8), but within individual regions, variation was not related to the rainfall or ANPP; uncertainty increases with movement toward smaller spatial scales. This would suggest the advisability of designing and evaluating adaptation strategies at more local scales.

Whether the recent drought (included in the 1997-2010 period) was the worst in the 112 years modelled here depended on the location. Across most of Western Australia and at Lameroo, the 1997-2010 period could reasonably be seen as part of a larger drying trend. In much of south-eastern Australia, on the other hand, the impact of the “millenium drought” may have been due as much to the sudden change from the relatively favourable conditions experienced in the late 1980s and 1990s as to departure from the long-term average climate. In central New South Wales, and especially at Armidale, there were other time periods when the profitability of present-day grazing systems would have been lower than during 1997-2010

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Appendix 6. Impacts of climate change to 2070 at eight locations across southern New South Wales: a preliminary analysis

<u>Introduction</u>

As part of the *Southern Livestock Adaptation 2030* program, the NSW Department of Industry & Investment (NSW I&I) has been using the GRAZPLAN simulation models to analyse the impacts of likely future climate change on a wide range of grazing systems, and also to explore possible options for adapting to these changes. The focus of I&I's work is on the relatively near term (i.e. climates projected for the year 2030). The brief of *Southern Livestock Adaptation 2030*, however, includes a requirement to consider climate changes over longer time frames (out to the year 2070).

This study uses simulation modelling to examine the likely impact of projected changes in climate and atmospheric CO_2 concentration at 2030, 2050 and 2070 on the dynamics of pastures across eight locations in southern New South Wales. Impacts on profitability (at constant prices) and on three important natural resource indicators (ground cover, deep drainage & livestock methane production) are considered. Adaptations to changing climate are limited to modification of stocking rates.

<u>Methods</u>

The GRAZPLAN simulation models of the dynamics of grazed temperate grasslands (Freer *et al.* 1997; Moore *et al.* 1997) were used in this study. These models are widely employed within Australia for purposes of research (e.g. Cayley *et al.* 1998; Clark *et al.* 2003; Mokany *et al.* 2010) and also in decision support for producers (Donnelly *et al.* 2002 and references therein; Warn *et al.* 2006).

The models' behaviour will respond to changes in climate and atmospheric CO_2 concentration in a variety of different ways. The GRAZPLAN accounts for four effects of increasing CO_2 concentration: reduced transpiration due to partial stomatal

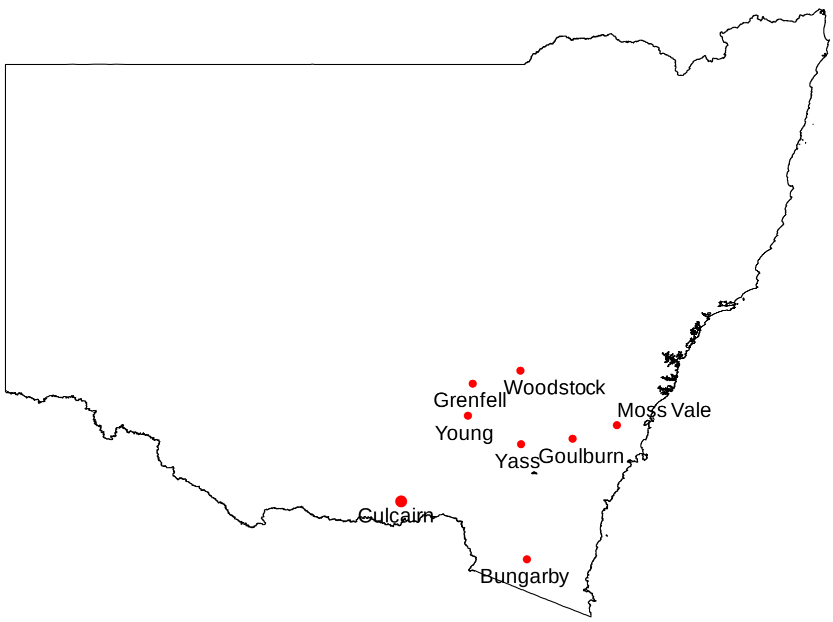

Figure A6.1. Map of the eight locations in southern NSW at which climate change impact simulations were carried out.

closure, a direct CO_2 fertilization effect, decreases in specific leaf area and decrease in leaf nitrogen content. Changes in rainfall at a location will mainly affect the dynamics of the models via the water balance. Effects of changes in soil water content on pasture growth rate and the decomposition of litter are represented in the pasture model. The key effects of increasing temperatures across southern Australia – at least for increases up to about 3°C – are also accounted for by model equations describing effects of increased temperatures on vapour pressure deficit, seed dormancy release, germination, plant phenology, rates of assimilation, respiration and decline in the digestibility of herbage (Moore et al. 1997), reductions in animal intakes on hot days, decreased energy expenditures by livestock in winter and lower peri-natal mortality of lambs (Freer et al. 1997). In the GRAZPLAN models, livestock methane emissions are predicted following Blaxter & Clapperton (1965).

Eight locations where NSW I&I officers have been carrying out climate change studies were selected for analysis (Figure A6.1). Annual rainfall at the locations ranges from medium (550 mm) to high (950 mm) and average annual temperature from a cold 11.5°C to a temperate 16.0°C (Table A6.1). For each of these eight locations, a set of representative grazing systems (soils, pastures, livestock, management and financial data) has been described as part of the NSW I&I *Southern Livestock Adaptation 2030* project. One representative grazing system per location was chosen for use in this study, and the input data required to simulate that grazing system with the GrassGro decision support tool (which implements the GRAZPLAN models) were provided by NSW I&I.

Details of the representative farms are given in Table A6.1. Sheep enterprises were selected where available (at 6 of the 8 locations) to keep the simulations as consistent as possible, but a high degree of diversity in animal and pasture genotypes and management practices was inevitably included.

A reference period of historical weather data (1970-1999) was simulated, plus projected future climates under the SRES A2 emissions scenario for the years 2030, 2050 and 2070. In order to take account of the uncertainty in projected climates, climate predictions from four global circulation models (GCMs) were considered for each future year: UKMO-HadGEM1 (Johns *et al.* 2006), CCSM3 (Collins *et al.* 2006), ECHAM5/MPI-OM (Roeckner *et al.* 2003) and GFDL-CM2.1 (Delworth *et al.* 2006). 13 climates (one historical and 12 projected futures) were therefore considered at each location.

Daily weather data sequences for each projected climate were constructed using a downscaling technique adapted from that of Zhang (2007). Briefly, the technique uses ranked monthly values from the historical weather record and outputs from a global circulation model to develop a locally-specific “transfer function” that maps the GCM-predicted monthly value to a location-specific monthly value. The resulting time sequences of monthly weather values are detrended when a weather sequence corresponding to the climate for a particular time is required, as in this study. Finally, a stochastic weather generator (Hansen and Mavromatis 2001) is used to convert the monthly time course of weather to daily values. Full details of the technique are given by Moore (2008). ISAM reference atmospheric CO_2 concentrations (Houghton *et al.* 2001) corresponding to the A2 scenario for each date were used (350 ppm for historical climate, 451 ppm for 2030, 532 ppm for 2050 and 635 ppm for 2070).

GrassGro (version 3.2.2) was used to carry out a simulation experiment with the following factors: location (8) x climate (13) x stocking rate (11-16 levels depending on the location). Four replicates of each combination of factors were simulated to reduce the small effects of random births & deaths on the flock/herd age structure.

Table A6.1. Attributes of the grazing systems that were analysed with the GRAZPLAN models at each of eight locations across southern NSW. PAWC = plant-available water-holding capacity

Location	Mean Annual Rainfall (mm)	Mean Annual Temperature (°C)	Soil	PAWC (mm)	Pasture species	Grazing enterprise	Lambing/ Calving Date
Bungarby	550	11.5	Stony chocolate soil of basaltic origin	119	*Poa sieberiana* *Austrostipa* spp. Annual legumes	Self-replacing Merino ewes, lambs sold at 14 months	16 Sep
Moss Vale	953	13.2	Yellow-grey duplex soil	195	Cocksfoot Perennial ryegrass White clover	British x Charolais cows, weaners sold at 9½ months	11 Aug
Goulburn	647	13.3	Shallow yellow-grey duplex soil	67	Phalaris Annual grass Subterranean clover	Self-replacing Merino ewes, lambs sold at 15 months	31 Aug
Yass	697	13.9	Sandy loam over heavy clay	113	Annual grass Subterranean clover	Self-replacing Merino ewes, lambs sold at 15 months	31 Aug
Woodstock	753	14.4	Light-textured brown chromosol	198	Phalaris Subterranean clover	First-cross ewes, lambs sold at 44 kg	12 Mar
Young (2-paddock system)	680	14.8	Gradational earth	114 162	60 % Annual grass Subterranean clover 40% Lucerne Annual grass	Angus cows, yearlings sold at 350-360 kg	11 Jul
Culcairn	616	15.3	Red duplex soil, hard-setting A horizon	105	Annual grass Subterranean clover	First-cross ewes, lambs sold at 6½-7½ months	28 Apr
Grenfell	641	16.0	Red duplex soil, hard-setting A horizon	120	Phalaris Annual grass Subterranean clover	Self-replacing Merino ewes, lambs sold at 5 months	20 Jul

Table A6.2. Costs and prices used to calculate financial returns. DW = dressed weight; LW = live weight

Enterprise		Fine-wool Merino		Medium-wool Merino & crossbred ewes	Cattle	
Location	Bungarby	Goulburn	Yass	Young, Woodstock, Culcairn	Moss Vale	Grenfell
Prices for:						
Female young stock	60.00 /head	35.00 /head	35.00 /head	3.61 /kg DW	1.98 /kg LW	1.68 - 2.02 /kg LW*
Male young stock	1.50 /kg LW	35.00 /head	35.00 /head	3.61 /kg DW	2.10 /kg LW	1.78 - 2.14 /kg LW*
Cull stock	3.00 /kg DW	1.80 /kg DW	1.80 /kg DW	1.82 /kg DW	1.27 /kg LW	1.30 /kg LW
Dressing percentage	42%	41%	41%	41%		
Skin price	1.00	5.00	5.00	5.00		
Wool price: 18 µ		1076		1130		
(¢/kg clean) 19 µ		976		977		
20 µ		885		840		
22 µ		838		762		
23 µ				738		
25 µ				695		
27 µ				492		
29 µ				462		
Average:fleece price		0.90		0.90		
Cost of shearing ($)		5.74		5.74		
Cost of wool sales		4%		4%		
Husbandry costs ($/yr):						
Adult stock		3.40		3.40	17.00	
Young stock		4.50		4.50	12.00	
Purchase costs ($):						
Ewes or cows		n/a		Merino 60 Crossbred 90	1000	
Rams or bulls	1200	800	800	800	4500	
Fixed cost of sales	3.00	2.00	2.00	2.00	37.00	
Variable cost of sales		5%		5%	5%	
Cost of maintenance supplement (¢/MJ)		2.5		Young 2.1 Woodstock 1.8 Culcairn 2.7	2.8	1.0

* Cattle prices at Grenfell vary by month

For each simulation, physical and financial outputs (rainfall, temperature, pasture growth rates and composition, conception and weaning rates, quantities of wool and livestock sales and amounts of supplementary feeding, income from wool and meat sales and costs associated with sales, animal husbandry, supplementary feeding and pasture management, ground cover, methane emissions and deep drainage) were recorded. Costs and prices used to compute economic returns are given in Table A6.2. A long-term rate of profit was calculated as the gross margin less $100/ha overheads and a further adjustment for the capital cost of the livestock required at each stocking rate (a 7% interest rate was assumed).

Within each location x climate combination, an "optimal sustainable" stocking rate was then identified as that rate which maximized long-term profit, subject to the constraint that ground cover (averaged over the farm) should be less than 0.70 on no more than 7% of days over a 30-year period. The sustainable optimal stocking rate was identified by interpolating between the gross margins and ground cover indices resulting from the simulations at each level of stocking rate. All results are presented at this stocking rate.

Results

Key indices describing the production and NRM outcomes of the eight grazing systems under historical weather conditions are shown in Table A6.3. Each of the representative grazing systems is profitable in the long term. Stocking rates are constrained by the requirement to maintain ground cover at 7 of the 8 locations (Moss Vale, the wettest location, being the exception). As expected, profit per hectare is quite closely related to pasture production (Figure A6.2(a)), with the cattle production system at Grenfell being something of an outlier.

Table A6.3. Production and NRM indices for eight NSW grazing systems modelled with the GrassGro decision support tool under historical (1970-1999) climate conditions and an atmospheric CO_2 concentration of 350 ppm. Stocking rates have been adjusted to thee "optimal sustainable" level as defined in the text. A.N.P.P. = aboveground net primary productivity; DSE = dry sheep equivalent.

Location	Enterprise	Mean Annual Rainfall (mm)	A.N.P.P. (t/ha)	Optimal Sustainable Stocking Rate	Clean wool production (kg/ha)	Total live weight sold (kg/ha)
Bungarby	Ewe	550	5.8	2.9	15.8	65
Moss Vale	Cattle	953	11.0	1.56		344
Goulburn	Ewe	674	6.9	5.7	34.2	180
Yass	Ewe	697	9.1	7.0	42.5	222
Woodstock	Ewe	753	8.5	5.9	19.3	360
Young	Ewe	680	8.8	8.1	35.0	190
Culcairn	Ewe	616	8.8	5.2	14.5	443
Grenfell	Cattle	641	6.8	0.62		157

Location	Enterprise	Profit/ha	Frequency (cover<0.7)	Deep Drainage (mm)	Methane per DSE (kg CH_4)
Bungarby	Ewe	85	0.07	30	8.0
Moss Vale	Cattle	301	0.05	171	7.6
Goulburn	Ewe	147	0.07	126	7.2
Yass	Ewe	215	0.07	21	7.2
Woodstock	Ewe	205	0.07	69	7.0
Young	Ewe	198	0.07	82	7.1
Culcairn	Ewe	164	0.07	80	6.7
Grenfell	Cattle	43	0.07	49	7.8

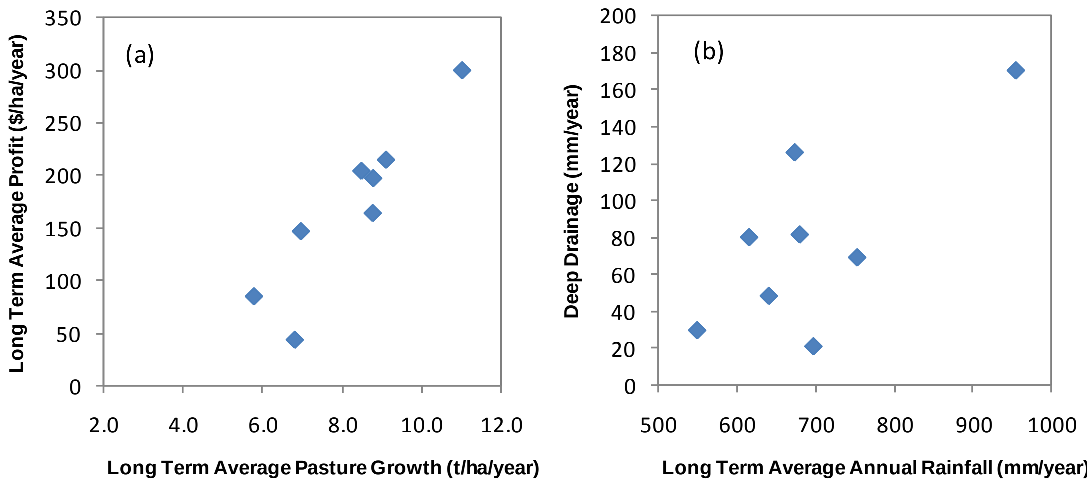

Figure A6.2. Relationships between (a) the long-term average profit and aboveground pasture growth and (b) long-term average deep drainage and rainfall, for eight NSW grazing systems under historical (1970-1999) weather conditions. Values are for the optimal sustainable stocking rate (as defined in the text).

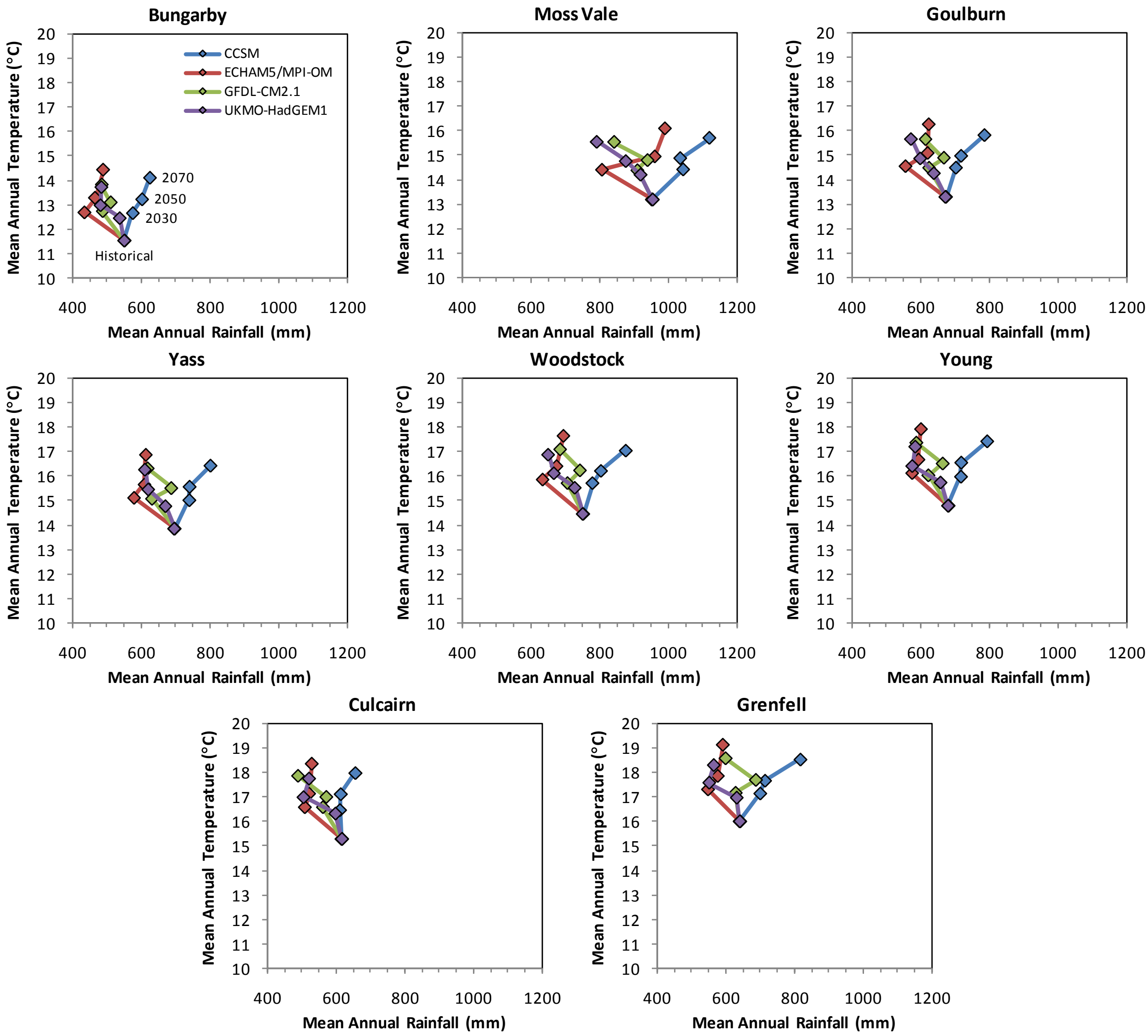

Figure A6.3. Changes in annual rainfall and temperature projected for eight locations in NSW by four global circulation models at 2030, 2050 and 2070. Historical average values (1970-1999) are at the root of each "tree", with the 2030, 2050 and 2070 projections for each GCM shown as a connected line.

There is a relationship between rainfall and deep drainage across sites, but it is not especially strong (R^2 = 0.53) owing to the diverse soil types on which the grazing systems operate. When expressed on a stocking intensity basis, methane production by livestock is quite stable across the eight locations (7-8 kg CH_4/DSE). The lower value at Culcairn is presumably caused by a higher ratio of young stock (which are more energetically efficient) to adult animals.

Climate changes

Figure A6.3 shows the changes in long-term average climate (rainfall and temperature) projected by the four GCMs out to 2070. The projected changes show a high degree of consistency across the eight locations. Under the SRES A2 emissions scenario, the ECHAM5/MPI-OM model predicts a substantial drying to 2030 that is partly recovered in 2050 and 2070 (at Moss Vale, a small increase relative to historic levels is predicted by this GCM at these two dates). CCSM3 predicts a steady increase in rainfall of 6-27% by 2070. The other two GCMs predict a drying trend (with an increase between 2030 and 2050 predicted by GFDL-CM2.1); by 2070 they project similar average annual rainfall to ECHAM5/MPI-OM at most locations.

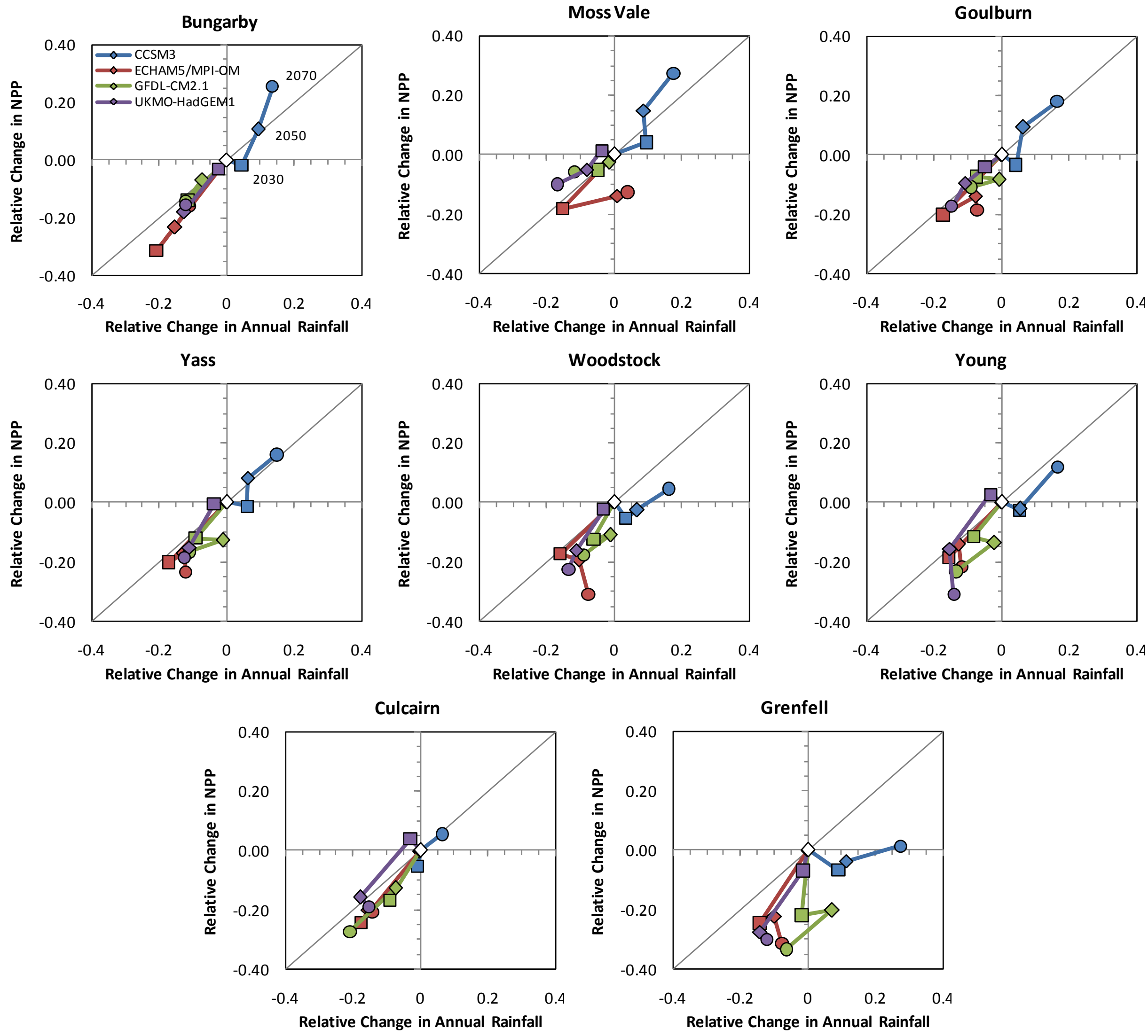

Figure A6.4. Relative change in long-term average aboveground net primary production projected for eight locations in NSW by four global circulation models at 2030, 2050 and 2070, as a function of relative change in long-term average annual rainfall. Historical average values (1970-1999, white diamonds) are at the root of each "tree", with the 2030, 2050 and 2070 projections for each GCM shown as a connected line. The diagonal line indicates equal relative rates of change.

Temperatures are predicted to rise consistently over time across all sites by all GCMs. Projected temperature increases range between 0.9-1.4°C at 2030, 1.5-2.0°C at 2050 and 2.2-3.2°C at 2070; they are largest for ECHAM5/MPI-OM (exacerbating the rainfall decreases predicted by this GCM) and smallest for UKMO-HADGEM1.

Pasture production

As can be seen from Figure A6.4, the projected changes in total rainfall largely determine the changes in pasture growth (aboveground net primary productivity) at all eight locations. At the majority of sites, a given relative change in rainfall is predicted to produce an approximately proportionate change in pasture growth; the main exceptions are the coldest, driest site (Bungarby) and the warmest site (Grenfell). At Bungarby, each 1% change in annual rainfall induces roughly 1.4% change in pasture growth. At Grenfell there is a substantial depression of overall pasture growth rate as temperatures increase (a 6-7% decrease in growth per degree of warming), with the result that relative changes in pasture production are

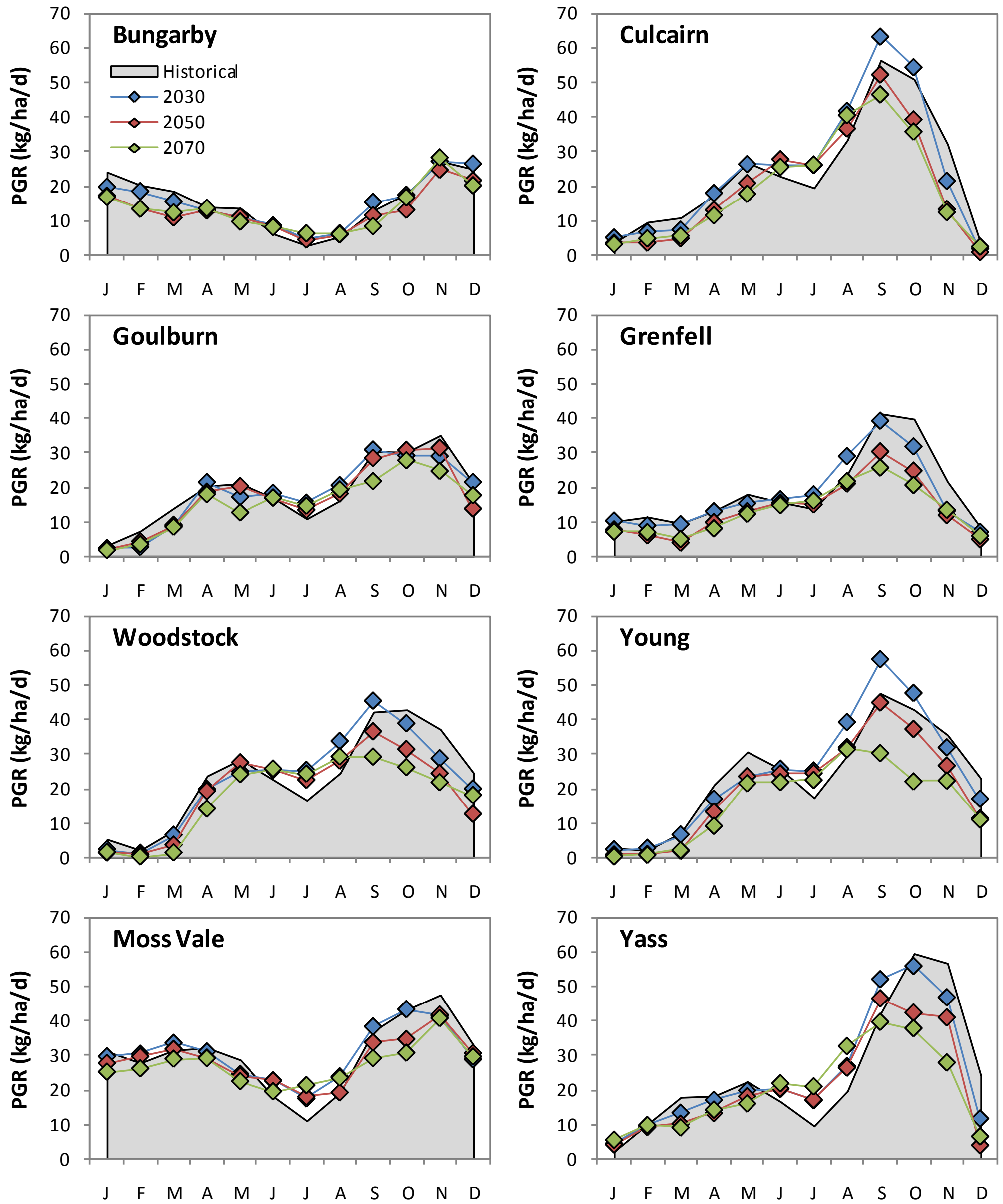

Figure A6.5. Modelled long-term average monthly pasture growth rates (PGR) at eight locations in NSW for climates projected by the UKMO-HADGEM1 model under the SRES A2 emissions scenario. Historical (1970-1999) growth rates for each month are shown as grey shaded areas for comparison.

displaced below the 1:1 line in Figure A6.4. There is some indication that a similar effect operates at the two other sites in the South-west Slopes (Woodstock and Young).

Figure A6.5 shows the projected long-term average patterns of monthly pasture growth rate for one global circulation model (UKMO-HADGEM1). Under this drying projected climate, there is a progressive reduction in the peak growth rate in spring, a shortening of the growing season and an increase in winter growth rates at most locations. At Grenfell, winter growth rates do not increase over time, which explains the decreases in total pasture growth there with increasing temperatures. At Young and Culcairn, growth rates in September-October increase at 2030 and then decrease at 2050 and 2070. The shifts in the projected pattern of pasture growth at Bungarby are distinct from the other 7 locations, with the largest reductions in growth occurring in summer and early autumn.

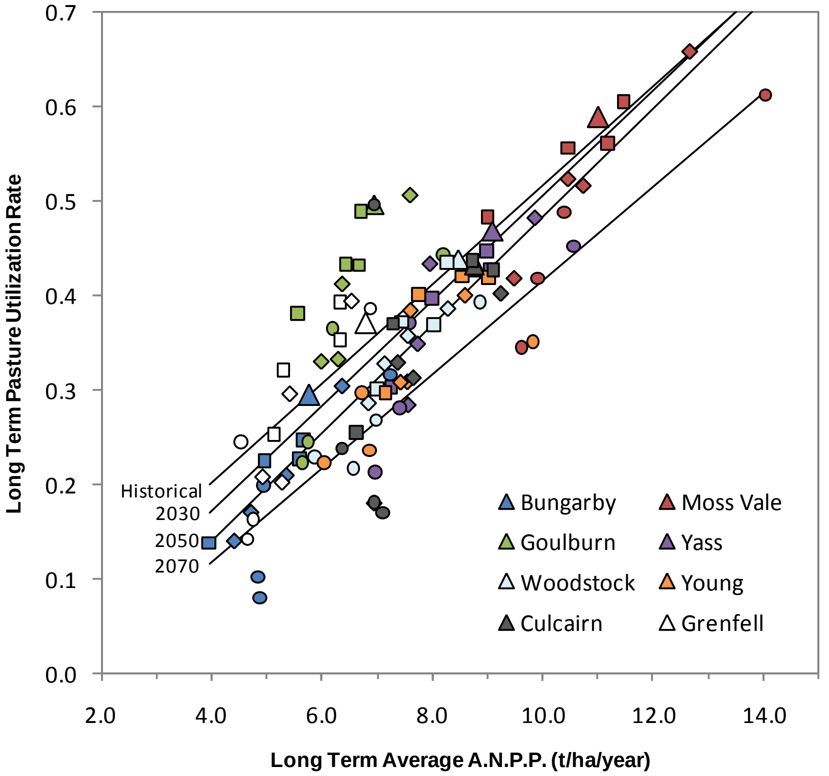

Figure A6.6. Relationships between long-term average pasture utilization rate and aboveground net primary productivity at eight locations in NSW (shown in different colours) for climates projected by four global circulation models under the SRES A2 emissions scenario. △ Historical climate; □ 2030 climates; ◇ 2050 climates; ○ 2070 climates. Regression lines for historical climate and for the three future years (with values for Goulburn excluded) are shown as black lines.

Pasture utilization

When the modelling results are compared at the sustainable optimum stocking rate, there is a strong positive relationship between the rate of pasture utilization (pasture consumed:pasture grown) and long-term average pasture ANPP (Figure A6.6) that is reasonably consistent across most of the locations and the 13 climates. The modelled results at Goulburn show a different relationship, however, with a much higher sustainable utilization rate relative to the level of ANPP under historical and 2030 climate. Especially at 2070, there is a tendency for the sustainable utilization rate to fall at a given level of ANPP (Figure A6.6).

Stocking rates and livestock productivity

Table A6.4 shows how changes in pasture growth translate into stocking rates, income from pasture production and finally profit, as averages across the eight sites. The direction of these changes is largely determined by the direction of change in rainfall: for projections derived from the CCSM3 global circulation model rainfall tends to increase and so stocking rate, gross income and profit all tend to rise (at least in 2050 in 2070). For the other three general circulation models, however, rainfall declines in all three future years translate into corresponding or somewhat larger declines in pasture growth. Stocking rates decline by a larger relative amount, since (as shown in Figure A6.6) the sustainable optimum stocking rate generally declines with decreasing pasture production. Income per DSE remains fairly stable, so that changes in gross income are similar in all cases to changes in stocking rate. Finally, owing to the effect of fixed and overhead costs, profit declines faster in relative terms than income

Table A6.4. Relative changes in key production parameters from historical conditions (1970-1999) to 2030, 2050 and 2070, averaged over eight locations in NSW

Year	Change in:	CCSM3	ECHAM5/ MPI-OM	GFDL-CM2.1	UKMO-HadGEM1
		Global Circulation Model			
2030	Rainfall (mm)	+0.05	-0.17	-0.07	-0.03
	Pasture growth (kg/ha/year)	-0.03	-0.22	-0.13	-0.01
	Stocking rate (DSE/ha)	-0.06	-0.47	-0.24	-0.08
	Gross income ($/ha)	-0.06	-0.46	-0.23	-0.07
	Profit ($/ha)	-0.16	-0.86	-0.49	-0.17
2050	Rainfall (mm)	+0.07	-0.10	-0.02	-0.13
	Pasture growth (kg/ha/year)	+0.04	-0.18	-0.11	-0.15
	Stocking rate (DSE/ha)	+0.06	-0.49	-0.27	-0.39
	Gross income ($/ha)	+0.07	-0.48	-0.25	-0.38
	Profit ($/ha)	+0.04	-0.93	-0.48	-0.79
2070	Rainfall (mm)	+0.16	-0.08	-0.12	-0.14
	Pasture growth (kg/ha/year)	+0.14	-0.22	-0.19	-0.21
	Stocking rate (DSE/ha)	+0.10	-0.63	-0.42	-0.60
	Gross income ($/ha)	+0.12	-0.62	-0.41	-0.59
	Profit ($/ha)	+0.11	-1.18	-0.84	-1.12

For two of the general circulation models (ECHAM5/ MPI-OM and UKMO-HadGEM1), the projected climates would result in widespread financial unviability of livestock production in the absence of further adaptation or price changes.

Deep drainage and methane emissions

The levels of deep drainage vary widely from location to location (Table A6.3). As with pasture growth, the projected changes in deep drainage are primarily driven by changes in rainfall; the size of the response differs sharply from location to location, depending on rainfall patterns and the water-holding capacity of the soil. The other two main changes that are expected to affect the water balance are higher evaporative demand due to higher temperatures and reductions in transpiration due to closure of stomata in the presence of higher atmospheric CO_2. These opposite effects produce inconsistent variation around the main rainfall response, depending on the GCM projection and the year (Figure A6.7).

None of the projected climate changes alter the overall quality of pasture consumed enough to shift the expected production of methane per DSE; as a result the projected changes in livestock methane emissions per hectare are almost entirely driven by the changes in the sustainable optimum stocking rate (Figure A6.8).

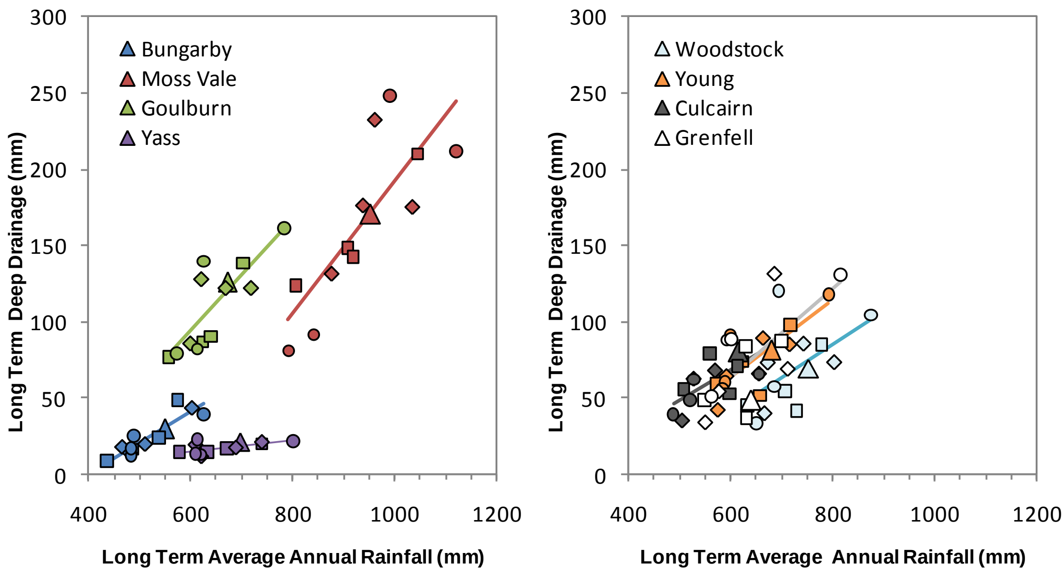

Figure A6.7. Relationships between long-term average deep drainage and rainfall eight locations in NSW (shown in different colours) for climates projected by four global circulation models under the SRES A2 emissions scenario. △ Historical climate; ☐ 2030 climates; ◇ 2050 climates; ○ 2070 climates. Regression lines each location (across historical and projected climates) are shown as coloured lines.

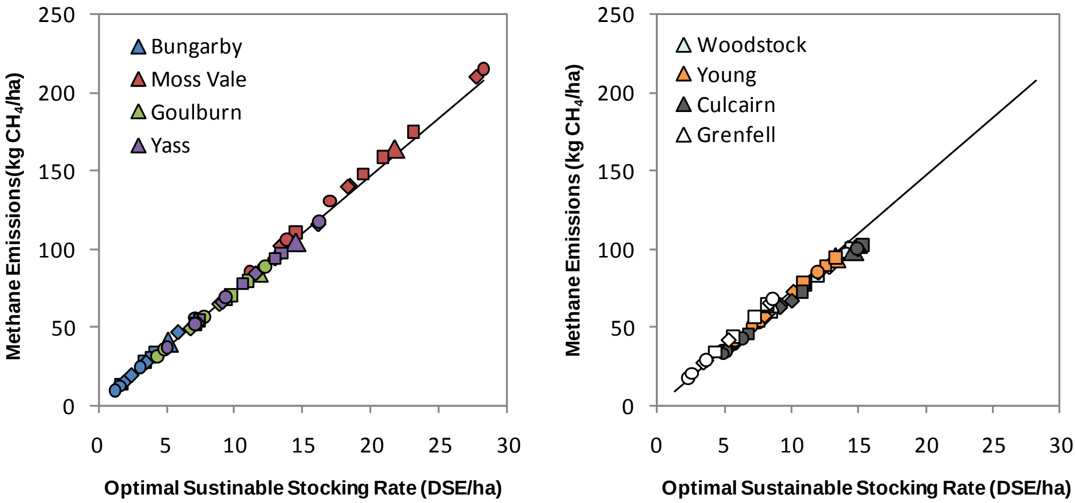

Figure A6.8. Relationships between long-term average methane emissions (on an area basis) and the optimal sustainable stocking rate, expressed as dry sheep equivalents per hectare, at eight locations in NSW (shown in different colours) for climates projected by four global circulation models under the SRES A2 emissions scenario. △ Historical climate; ☐ 2030 climates; ◇ 2050 climates; ○ 2070 climates. A common regression across all location and climates is shown as a black line.

Discussion

This modelling study has shown that, without doubt, rainfall outcomes will dominate the impacts of a changing climate on the functioning of livestock production systems in southern NSW. Other, more certain impacts (increasing CO_2 concentrations and temperatures) will have secondary effects. It is to be hoped, therefore, that the new round of GCM projections being prepared for the next Assessment Report of the IPCC will deliver smaller levels of uncertainty in their predictions of future rainfall in Australia's agricultural areas.

Across southern NSW, there was a general similarity in the impacts of climate change of the pasture-livestock systems. For three of the GCMs, profits are predicted to decrease sharply over the next six decades owing to decreasing rainfalls producing a disproportionate reduction in sustainable stocking rates (in the absence of other adaptations). Under the climate changes projected by the CCSM3 model, profitability decreases at the majority of sites in 2030 due to less efficient use of rainfall for pasture growth, but at 2050 and 2070 rainfall is projected to increase and this brings stocking rates and profitability back up. Within this general picture, however, each location exhibited individual features, for example the lack of an increase in winter growth rates at Grenfell (Figure A6.5), the shift in month-to-month patterns of pasture growth at Bungarby that was different to all other sites (Figure A6.5) or the insensitivity of deep drainage rates to changes in Rainfall at Yass (Figure A6.7).

Where they can be compared, the results of this study are broadly similar to the results reported for pasture growth changes by Cullen *et al.* (2009), who used different climate projections, a different downscaling technique and a different pasture growth model. For example Cullen *et al.* (2009) report a 5% increase in annual ANPP for Wagga Wagga at 2030 based on a 0.7°C temperature increase and an 8% rainfall decrease; this can be compared to a 4% increase found here for Culcairn (also in the Riverina) using projections for 2030 from GFDL-CM2.1, which imply 1.0°C temperature increase and a 3% rainfall decrease.

It is important to understand that this analysis is an impacts study only. A range of different adaptation options may ameliorate these climate change impacts. It appears, however, that the balance of risk is on the downside and that such adaptive management changes (or ways of increasing product prices relative to input costs) will need to be found and put into practice by livestock producers across southern NSW.

Livestock methane emissions per DSE were very stable across the range of climates & pasture types in southern NSW considered here. We can expect methane emission outcomes under a changing climate to be driven by stocking rate changes, and to a lesser extent by adaptive shifts in flock or herd structures.

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Model results from the UKMO-HADGEM1 model are Crown Copyright 2005, data provided by the Met Office Hadley Centre. We also record our appreciation to the teams responsible for the other three GCMs for making their modelling results available for our research.

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Appendix 7. Impacts of climate change across southern Australia in 2030, 2050 and 2070

Introduction

As part of the *Southern Livestock Adaptation 2030* program, extension and industry development officers from New South Wales, Victorian, Tasmanian, South Australian and Western Australian state agencies have used the GRAZPLAN simulation models to analyse the impacts of likely future climate change on a wide range of grazing systems, and also to explore possible options for adapting to these changes. The focus of State-based analyses has been on the relatively near term (i.e. climates projected for the year 2030). The brief of *Southern Livestock Adaptation 2030*, however, includes a requirement to consider climate changes over longer time frames (out to the year 2070).

This study therefore uses simulation modelling to examine the likely impact of projected changes in climate and atmospheric CO_2 concentration at 2030, 2050 and 2070 on the dynamics of pasture and livestock production at 25 locations across southern Australia. Impacts on total income from 5 representative livestock production systems (Merino ewes, crossbred ewes, beef cows, wethers and steers) are considered. In this Appendix, adaptations to changing climate are limited to modification of stocking rates; a wider range of adaptations is considered in Appendix 8.

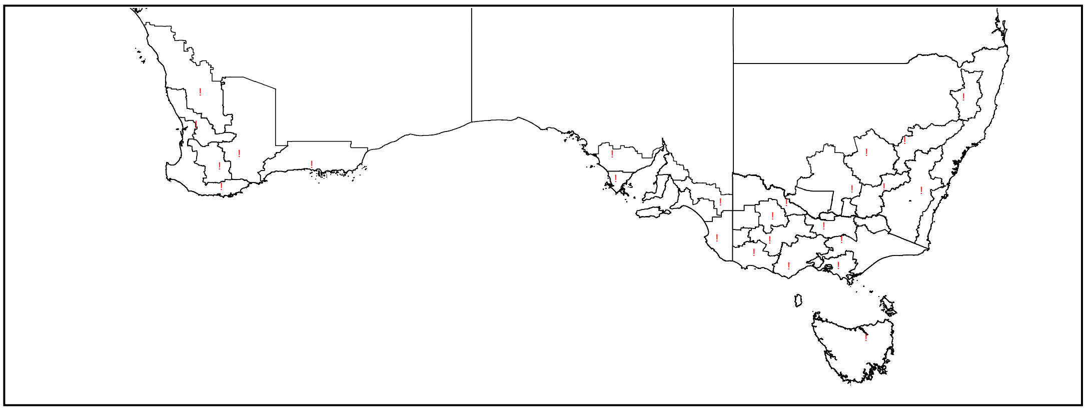
Methods

The GRAZPLAN simulation models of the dynamics of grazed temperate grasslands (Freer *et al.* 1997; Moore *et al.* 1997) were used in this study. These models are widely employed within Australia for purposes of research (e.g. Cayley *et al.* 1998; Clark *et al.* 2003; Mokany *et al.* 2010) and also in decision support for producers (Donnelly *et al.* 2002 and references therein; Warn *et al.* 2006).

The models' behaviour responds to changes in climate and atmospheric CO_2 concentration in a variety of different ways. The GRAZPLAN pasture model accounts for four effects of increasing CO_2 concentration: a direct CO_2 fertilization effect, reduced transpiration due to partial stomatal closure, decreases in specific leaf area and decrease in leaf nitrogen content. Changes in rainfall at a location will mainly affect the dynamics of the models via the water balance. Effects of changes in soil water content on pasture growth rate and the decomposition of litter are represented in the pasture model. The key effects of increasing temperatures across southern Australia – at least for increases up to about 3°C – are also accounted for by model equations describing effects of increased temperatures on vapour pressure deficit, seed dormancy release, germination, plant phenology, rates of assimilation, respiration and decline in the digestibility of herbage (Moore et al. 1997), reductions in animal intakes on hot days, decreased energy expenditures by livestock in winter and lower peri-natal mortality of lambs (Freer *et al.* 1997). In the GRAZPLAN models, livestock methane emissions are predicted following Blaxter & Clapperton (1965).

Statistical Areas Level 2 from the new Australian Statistical Geography Standard (Australian Bureau of Statistics 2011) were grouped into a set of 43 regions with approximately equal Gross Value of Agricultural Production (GVAP, based on Australian Bureau of Statistics 2006). SA2s were grouped together into regions with similar climate and broadacre land use (i.e. the proportion of GVAP attributable to cropping, sheep and cattle production). A subset of 28 of these regions, covering temperate southern Australia, was included in this study; however 5 regions in the wheatbelt of WA, where cropping dominates over livestock production, were

Figure A7.1. Map of the 25 locations across southern Australia at which climate change impact simulations were carried out, together with the regions which each location has been selected to represent. See Appendix 11 for details of the locations.



combined into 2, so producing a final set of 25 regions (Figure A7.1). Within each of the 25 regions, a single Australian Bureau of Meteorology weather station was selected as a representative location at which modelling analyses were carried out (Figure A7.1; Appendix 11). Annual rainfall at the locations ranges from 299 to 1091 mm, rainfall pattern from highly winter-dominant to moderately summer-dominant and average annual temperature from 11.6°C to 19.1°C (Appendix 11).

For each location, a representative set of land resources (weather, soils and pastures) was described using the attributes required by the GRAZPLAN simulation models. Where possible, the soil and pasture information was drawn from GrassGro farm systems developed by State agency officers as part of their modelling work in *Southern Livestock Adaptation 2030*. For the remaining locations, the survey of Forrest *et al.* (1985) and the APSoil data base (www.apsim.info/wiki/APSoil.ashx) were drawn upon to develop soil descriptions, and information about representative pasture types was inferred from the NPICC pastures database (Pearson *et al.* 1997). At 7 of the locations, a forage base with more than one pasture type was used in the modelling studies (Appendix 11).

A set of 5 livestock enterprises was modelled at each of the 25 locations:

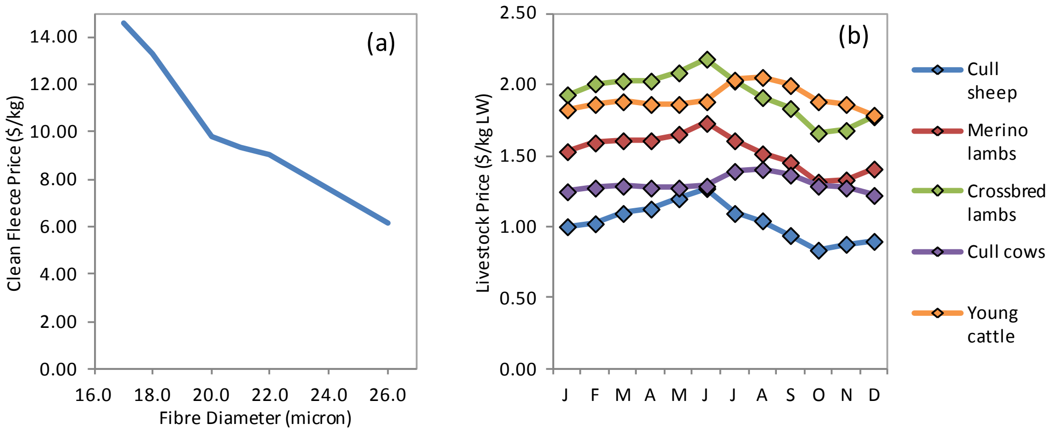
Merino ewes:	a self-replacing flock of medium-sized Merino ewes growing fine wool and mated to rams of the same genotype
Crossbred ewes:	a flock of Merino x Border Leicester cross ewes mated to Border Leicester rams each year and with replacement ewes purchased
Beef cattle:	a self-replacing herd of Angus cattle mated to bulls of the same genotype
Wethers:	a flock of Merino wethers for fine wool production, with the same genotype as the Merino ewe enterprise
Steers:	Angus steers purchased once each year and (usually) sold within 12 months of purchase, with the same genotype as the beef cattle enterprise

In order to facilitate comparisons between regions, the same livestock genotypes, prices for livestock and wool and variable costs of production were assumed within each enterprise across all locations (Table A7.1; Figure A7.2). Angus cattle were selected as this is now the single most common breed across Southern Australia.

Table A7.1. Attributes of the livestock genotypes simulated for each of the 4 modelled enterprises. The same genotype was used for each enterprise across all 25 locations.

	Merino ewes	Crossbred ewes	Beef cows	Wethers
Ewe or cow genotype	Merino	Border Leicester x Merino	Angus	Merino
Standard reference weight (kg)	50.0	60.0	550.0	50.0
Ram or bull genotype	Merino	Border Leicester	Angus	
Standard reference weight (kg)	70.0	84.0	770.0	
Reference fleece weight (kg greasy)	5.00	5.00		5.00
Reference wool fibre diameter (µm)	19.0	23.0		19.0
Adult mortality rate (/year)	4%	4%	2%	4%
Weaner mortality rate (/year)	5%	5%	2%	5%

Figure A7.2. Prices used in the climate change impacts modelling. (a) Clean fleece prices used for all sheep enterprises. (b) Sale prices ($/kg live weight) for the different classes of livestock.



Management policies (livestock replacement, the timing of the reproductive cycle, the sale of young stock and thresholds for supplementary feeding) were described separately for each of the 125 location x enterprise combinations. Once again, information was drawn from GrassGro farm systems developed by State agency officers where possible; otherwise expert opinion, literature accounts and test simulations with GrassGro were used to derive sensible values. Beef cattle production systems are highly diverse within regions (AusVet Animal Health Services 2006) and are also uncommon in some of the regions that were modelled, and so the systems modelled here for the beef cow enterprise are necessarily less representative of regional practice.

The date and age at purchase of crossbred ewes, steers and wethers at each location were set to be compatible with the reproductive cycle of the Merino ewe, beef cow and Merino ewe enterprises respectively. The same supplementary feed was used for all enterprises at a location, although the rules for feeding differed between enterprises. At locations in the cereal-livestock zone, the availability of stubbles was modelled by removing livestock from the paddocks when there was less than 800 kg/ha of available green herbage in any paddock, and providing them with an *ad libitum* diet approximating that which can be expected for sheep or cattle on stubbles (ME content 8.6 MJ/kg DM for sheep and 8.3 MJ/kg DM for cattle, 14% crude protein). Further details of the 125 livestock management systems are given in Appendix 11.

A reference period of historical weather data (1970-1999) was simulated, plus projected future climates under the SRES A2 emissions scenario for the years 2030, 2050 and 2070. In order to take account of the uncertainty in projected climates, climate predictions from four global circulation models (GCMs) were considered for each future year: UKMO-HadGEM1 (Johns *et al.* 2006), CCSM3 (Collins *et al.* 2006), ECHAM5/MPI-OM (Roeckner *et al.* 2003) and GFDL-CM2.1 (Delworth *et al.* 2006). 13 climates (one historical and 12 projected futures) were therefore considered at each location.

Daily weather data sequences for each projected climate were constructed using a downscaling technique adapted from that of Zhang (2007). Briefly, the technique uses ranked monthly values from the historical weather record and outputs from a global circulation model to develop a locally-specific “transfer function” that maps the GCM-predicted monthly value to a location-specific monthly value. The resulting time sequences of monthly weather values are detrended when a weather sequence corresponding to the climate for a particular time is required, as in this study. Finally, a stochastic weather generator (Hansen and Mavromatis 2001) is used to convert the monthly time course of weather to daily values. Full details of the technique are given by Moore (2008). ISAM reference atmospheric CO_2 concentrations (Houghton *et al.* 2001) corresponding to the A2 scenario for each date were used (350 ppm for historical climate, 451 ppm for 2030, 532 ppm for 2050 and 635 ppm for 2070).

GrassGro (version 3.2.6) was used to carry out a simulation experiment with the following factors: location (25) x climate (13) x livestock enterprise (5) x stocking rate (9-18 levels). For each simulation, physical and financial outputs (rainfall, temperature, pasture growth rates and composition, conception and weaning rates, quantities of wool and livestock sales and amounts of supplementary feeding, income from wool and meat sales and costs associated with sales, animal husbandry, supplementary feeding and pasture management, ground cover, methane emissions and deep drainage) were recorded.

For each simulation run, an operating profit, *OP* ($/ha) was calculated as:

$$OP = \quad INCOME - \left(COST_{var} + COST_{fert} + COST_{stock} + COST_{operator}\right)$$

where

$INCOME$	is the total income per hectare from meat and wool from the enterprise
$COST_{var}$	is the variable costs per hectare of the enterprise, including costs of: animal husbandry, supplementary feed, shearing, purchase and sale of livestock (including rams or bulls) and sale of wool
$COST_{fert}$	is the cost per hectare of the P fertilizer required to maintain soil nutrient status
$COST_{stock}$	is the marginal capital cost of livestock per hectare
$COST_{operator}$	is an operator allowance (the equivalent cost of the farmer’s labour)

Variable costs were calculated using the same cost structure for each enterprise (and, where applicable, across enterprises). The annual cost of phosphorus fertilizer in each simulation was estimated from the maintenance P requirement for each paddock, calculated from the long-term average dry sheep equivalents grazing the paddock using the approach of Cayley and Quigley (2005). The marginal cost of extra livestock was accounted for in the operating profit in order to make financial comparisons between different stocking rates more meaningful. This cost was expressed relative to the capital cost of livestock at the sustainable optimal stocking rate for historical climate, and was calculated as the product of a capital value per head and an interest rate (7%). A fixed operator allowance of $60,000 was assumed for all locations and enterprises. This allowance was, however, spread across very different property areas at the different locations (Appendix 11).

Within each location x climate x enterprise combination, an “optimal sustainable” stocking rate was then identified as that rate which maximized long-term profit, subject to the constraint that ground cover (averaged over the farm) should be less than 0.70 on no more than a threshold proportion of days over a 30-year period. All results are presented at the optimal sustainable stocking rate.

The permitted frequency of low ground cover was varied across the locations according to the equation:

$$Threshold = \max\left(0.070,\ 0.82 \times \max\left(1 - \frac{AOR}{461}, 0\right)^2 + 0.046\right)$$

where *AOR* is the average April-October rainfall over the period 1970-1999. The threshold frequency of low ground cover varied from 0.07 at the 12 locations with *AOR*>385 mm to 0.27 at Kyancutta (*AOR*=218 mm).

<u>Results</u>

Figure A7.3 shows the modelled annual above-ground net primary productivity (ANPP) for the 25 locations over the historical (1970-1999) period. As expected, there is a gradient of decreasing ANPP from coastal to inland locations that is governed by rainfall. ANPP at some locations (e.g. Armidale and Wellington) is relatively low for their rainfall because the modelled feedbase at these locations includes native pastures that are managed at low levels of fertility.

Changes in ANPP across southern Australia under the 12 projected climates are shown in Figure A7.4. There are significant differences between the GCMs at each future date. For example, under projections from the CCSM3 model the total (area-weighted) pasture ANPP in the study area is modelled to decrease by 7% in 2050 and 8% in 2070, while for GFDL-CM2.1 total pasture ANPP is estimated to decrease by 20% in 2050 and 34% in 2070.

Figure A7.3. Modelled annual ANPP at 25 locations across southern Australia for the 1970-99 period, averaged over the 5 livestock enterprises at their optimal sustainable stocking rates. Note that while regions are shaded in this and following figures, values have been modelled for the representative location in that region (shown by a circle).

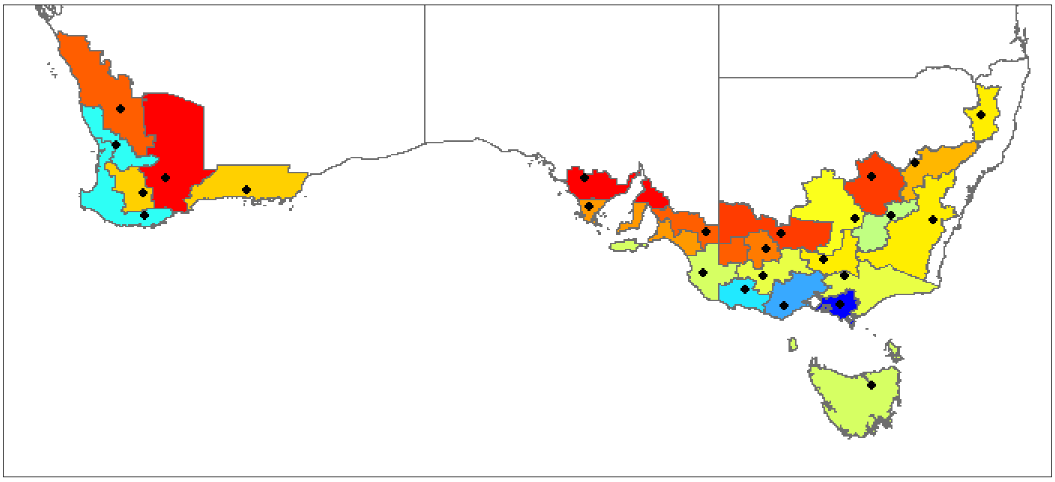


Figure A7.4. Modelled changes in aboveground net primary productivity of pastures across southern Australia resulting from climate changes projected by 4 GCMs under the SRES A2 scenario. Values shown are changes relative to ANPP in the 1970-1999 base scenario (Figure A7.3). ANPP values are averaged over the 5 livestock enterprises at their optimal sustainable stocking rates.

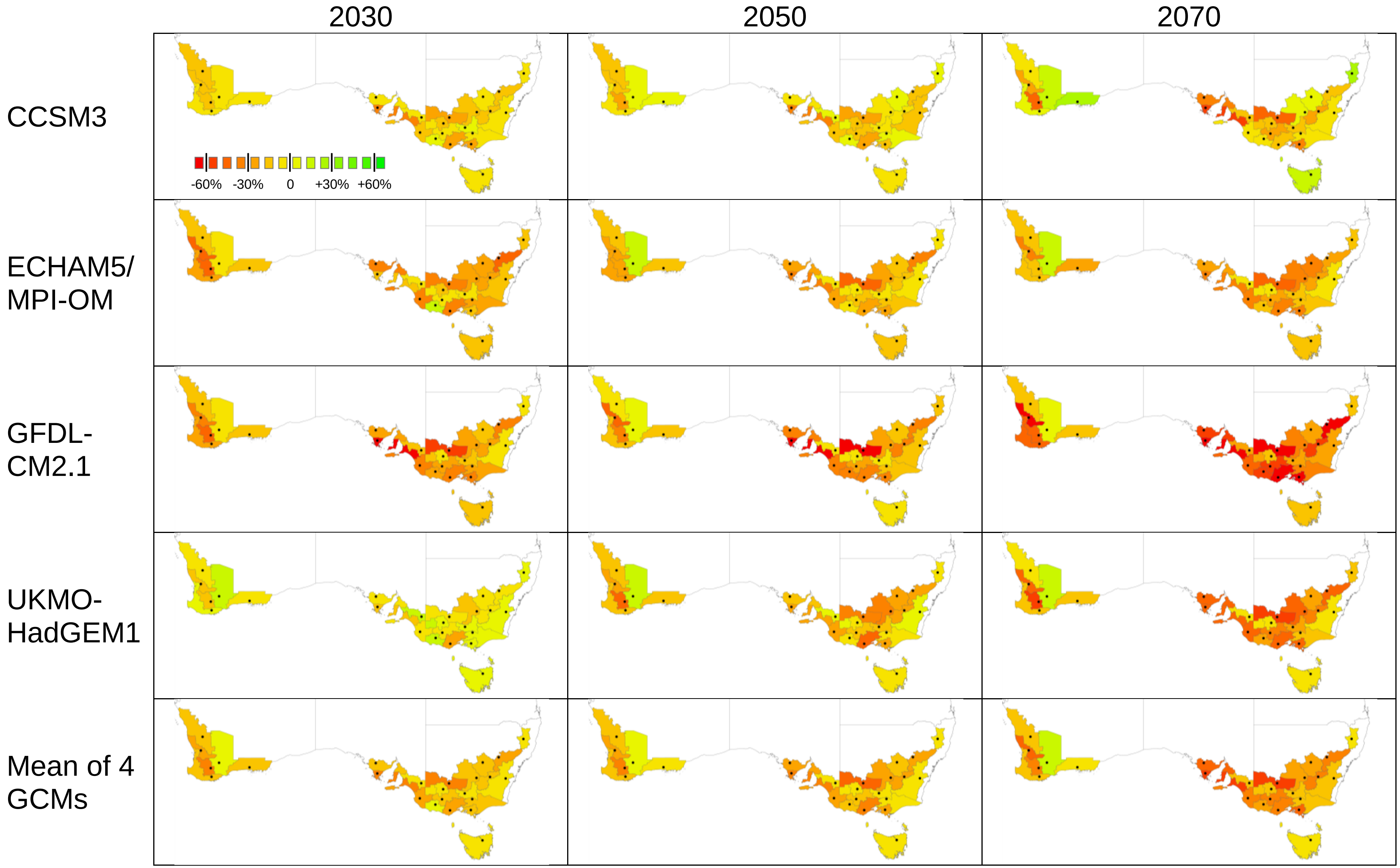
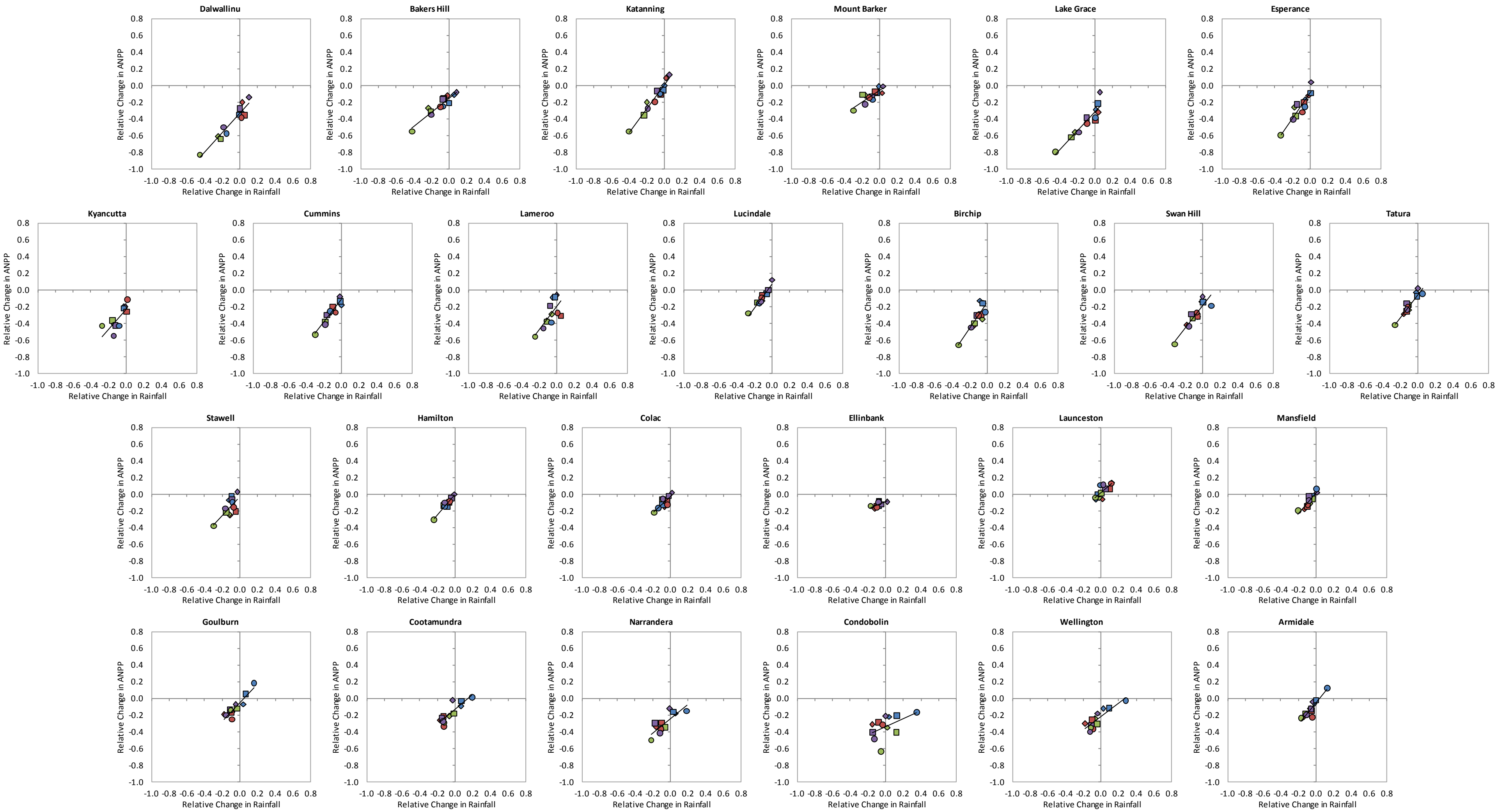


Figure A7.5. Relationships between proportional change in annual rainfall (relative to the 1970-1999 base period) and proportional change in aboveground net primary productivity of pastures. ANPP values are for the Merino ewe enterprise at its optimal sustainable stocking rate. Symbols denote ■ CCSM3, ■ ECHAM5/ MPI-OM, ■ GFDL-CM2.1, ■ UKMO-HadGEM1; ◆ 2030, ■ 2050, ● 2070. Locations are arranged geographically.



There is, however, a strong tendency for locations with lower annual rainfall to show larger decreases in annual ANPP. Since Western Australia has a larger area of low-rainfall land than the other states, it shows larger overall declines in ANPP across most combinations of GCM and future date (at Lake Grace, ANPP decreases by more than 40% at 2070 under all 4 GCMs). The same can be said – with lower confidence – for locations at the low-rainfall edge of the eastern Australian cereal-livestock zone (Kyancutta, Lameroo, Swan Hill, Narrandera and Condobolin). Conversely, the high-rainfall areas of southern Victoria show smaller decreases and some increases in ANPP; ANPP for the Tasmanian location (Launceston) is predicted to increase under 10 of the 12 projected climates.

Figure A7.5 shows that changes in rainfall are the main determinant of the modelled ANPP changes at most locations. Correlations between the projected change in rainfall and the modelled change in ANPP are above 0.45 at all locations except Condobolin. In Figure A7.6(a), it can be seen that the sensitivity of ANPP to changes in rainfall (i.e. the slope of the regression lines in Figure A7.5) tends to be greater in low-rainfall environments. ANPP reduces by more than 1.5 units for every unit of (annual) rainfall reduction at several locations with April-October rainfall below 400 mm, while at the wettest location (Ellinbank) this sensitivity is only 0.38. When the effects of rainfall changes are factored out, climate change tends to decrease ANPP at warmer locations (Figure A7.6(b)).

For the majority of location x projected climate combinations, the optimal sustainable stocking rates were lower than the historical value. As a result, the total quantity of pasture consumed by livestock was generally lower under the projected future climates (points below the X-axis in Figure A7.7; total pasture intake was lower in between 82% and 97% of cases, depending on the livestock enterprise). In the vast majority of enterprise x location x projected climate combinations – especially in 2050 and 2070 – the proportion of pasture growth that was consumed was lower than in the historical simulation (points below the 1:1 lines in Figure A7.7).

Figure A7.6. Cross-location comparisons of the overall climate change responses of pasture aboveground net primary productivity. (a) Relationship between the sensitivity of ANPP to change in rainfall and historical mean growing season rainfall. (b) Relationship between the relative change in ANPP when normalized to zero rainfall change and historical mean annual temperature. Normalized ANPP changes are estimated as the intercept from a linear regression over three future dates (2030, 32050 and 2070) and 4 GCMs.

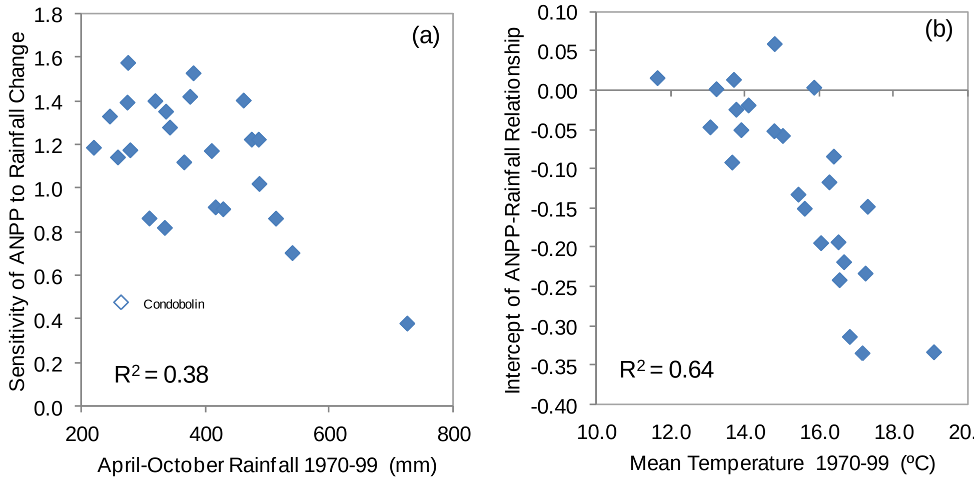


Figure A7.7. Relationships between proportional change in annual ANPP (relative to the 1970-1999 base period) and proportional change in the quantity of pasture eaten by livestock in the Merino ewe enterprise at the sustainable optimal stocking rate. ANPP values are those for the Merino ewe enterprise at its optimal sustainable stocking rates. Symbols denote ■ CCSM3, ■ ECHAM5/ MPI-OM, ■ GFDL-CM2.1, ■ UKMO-HadGEM1; ◆ 2030, ■ 2050, ● 2070. Locations are arranged geographically.

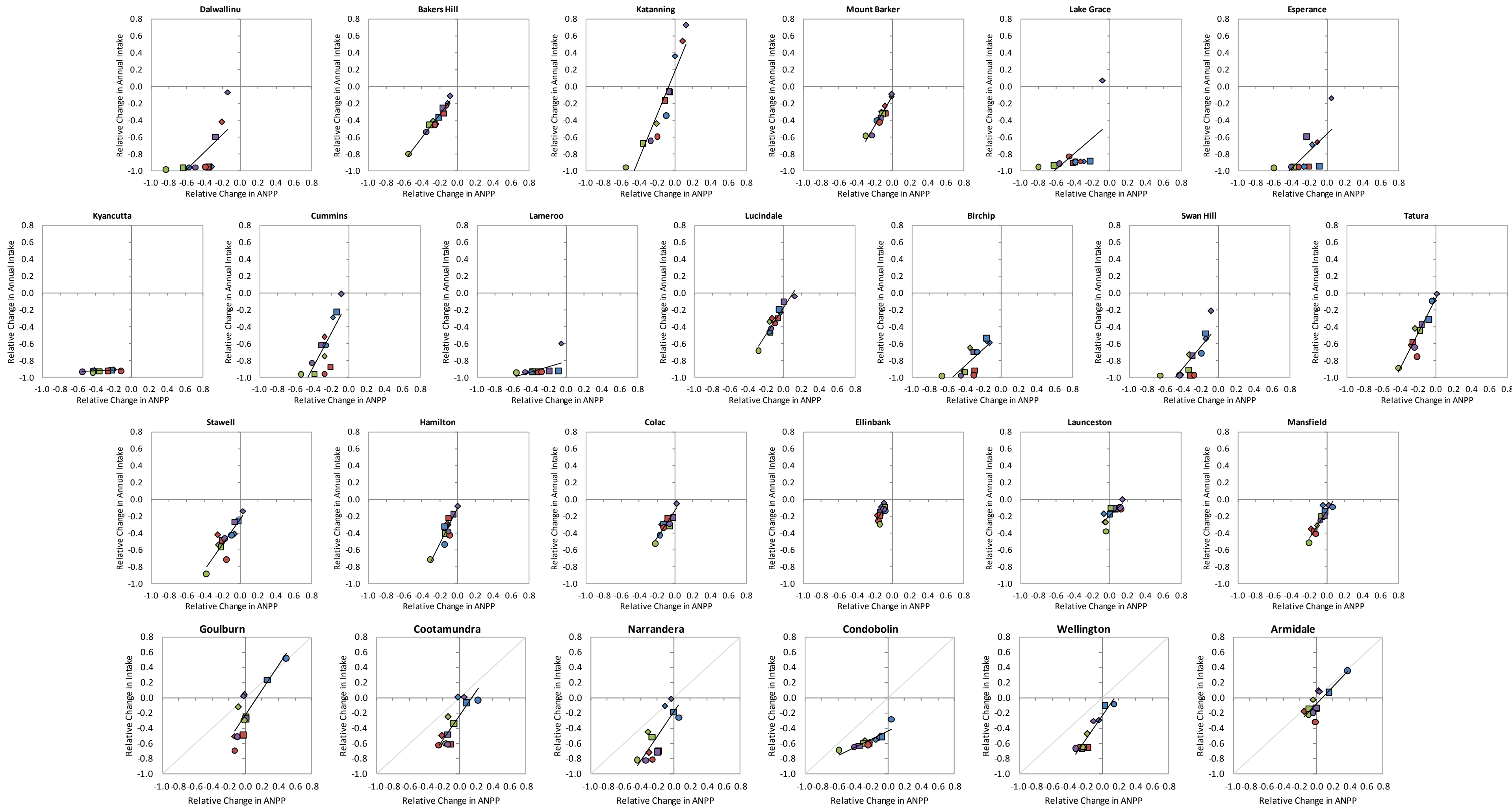


Figure A7.8. Relationship between relative change in total income and relative change in total pasture consumed by livestock for Merino ewe enterprises at 25 locations across southern Australia for climate changes at 2030, 2050 and 2070 projected by 4 GCMs under the SRES A2 scenario. Values shown are changes relative to the 1970-1999 base scenario and are computed at the optimal sustainable stocking rate for the relevant scenario.

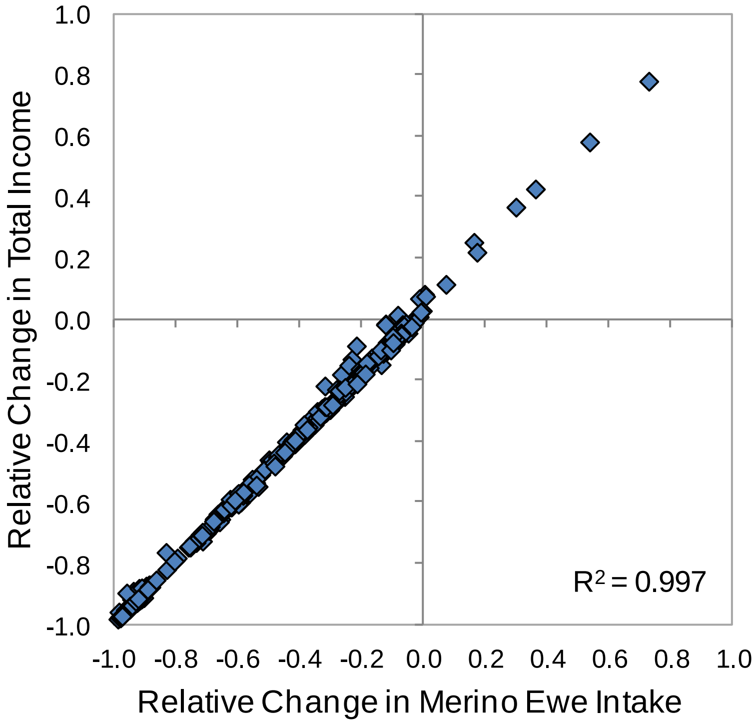


Figure A7.9. Modelled changes in total income from Merino ewe enterprises modelled across southern Australia resulting from climate changes projected by 4 GCMs under the SRES A2 scenario. Values shown are changes relative to average annual income modelled for the 1970-1999 base scenario (Figure 3). All incomes are computed at the optimal sustainable stocking rate for the relevant scenario. Note that the shading scale is different to that in Figure A7.4.

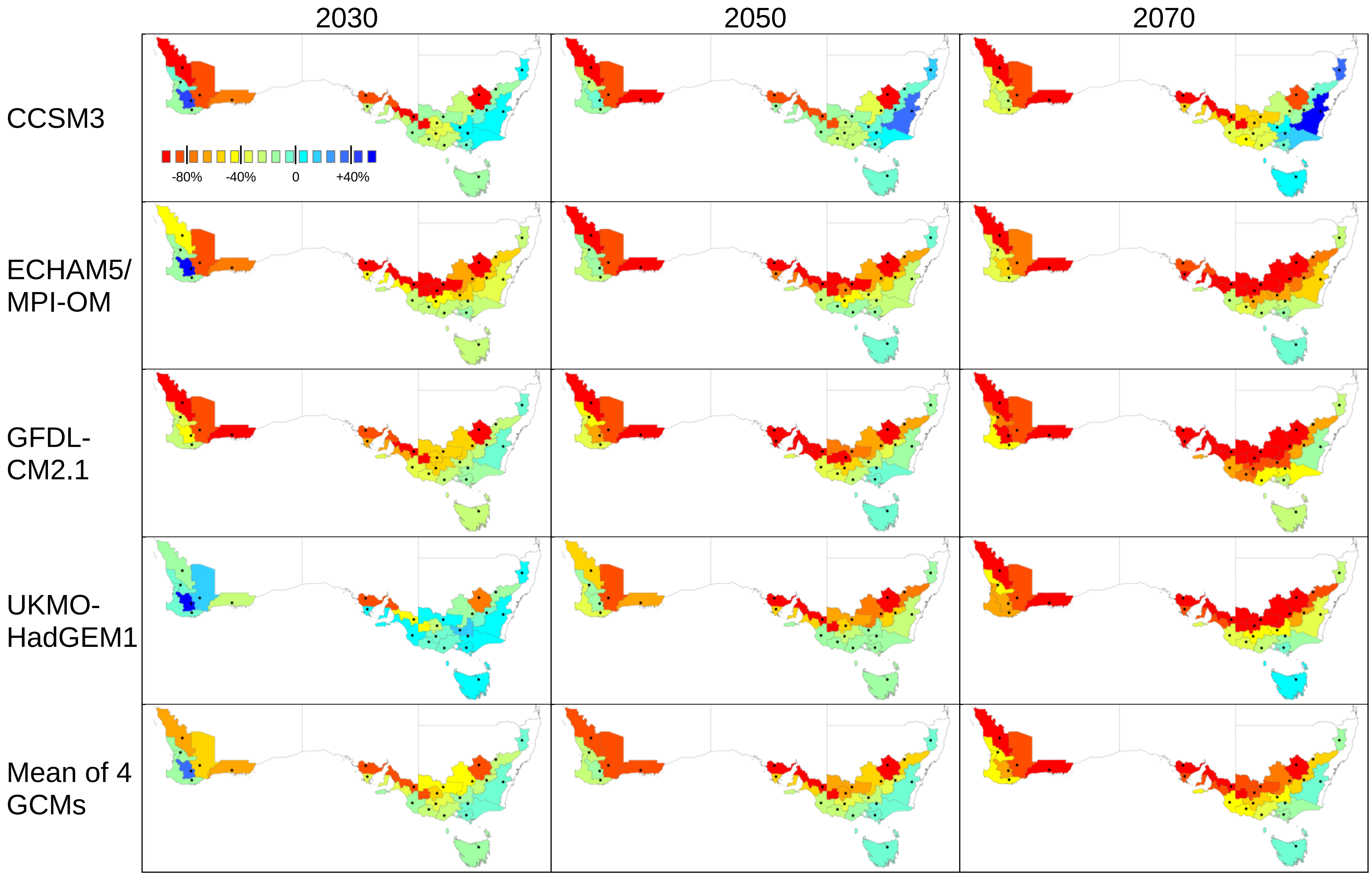


Figure A7.10. Modelled changes in long-term average operating profit from Merino ewe enterprises modelled across southern Australia resulting from climate changes projected by 4 GCMs under the SRES A2 scenario. Values shown are changes relative to average annual profit modelled for the 1970-1999 base scenario. All profits are computed at the optimal sustainable stocking rate for the relevant scenario. Note that the shading scale is different to that in Figures A7.4 and A7.9.

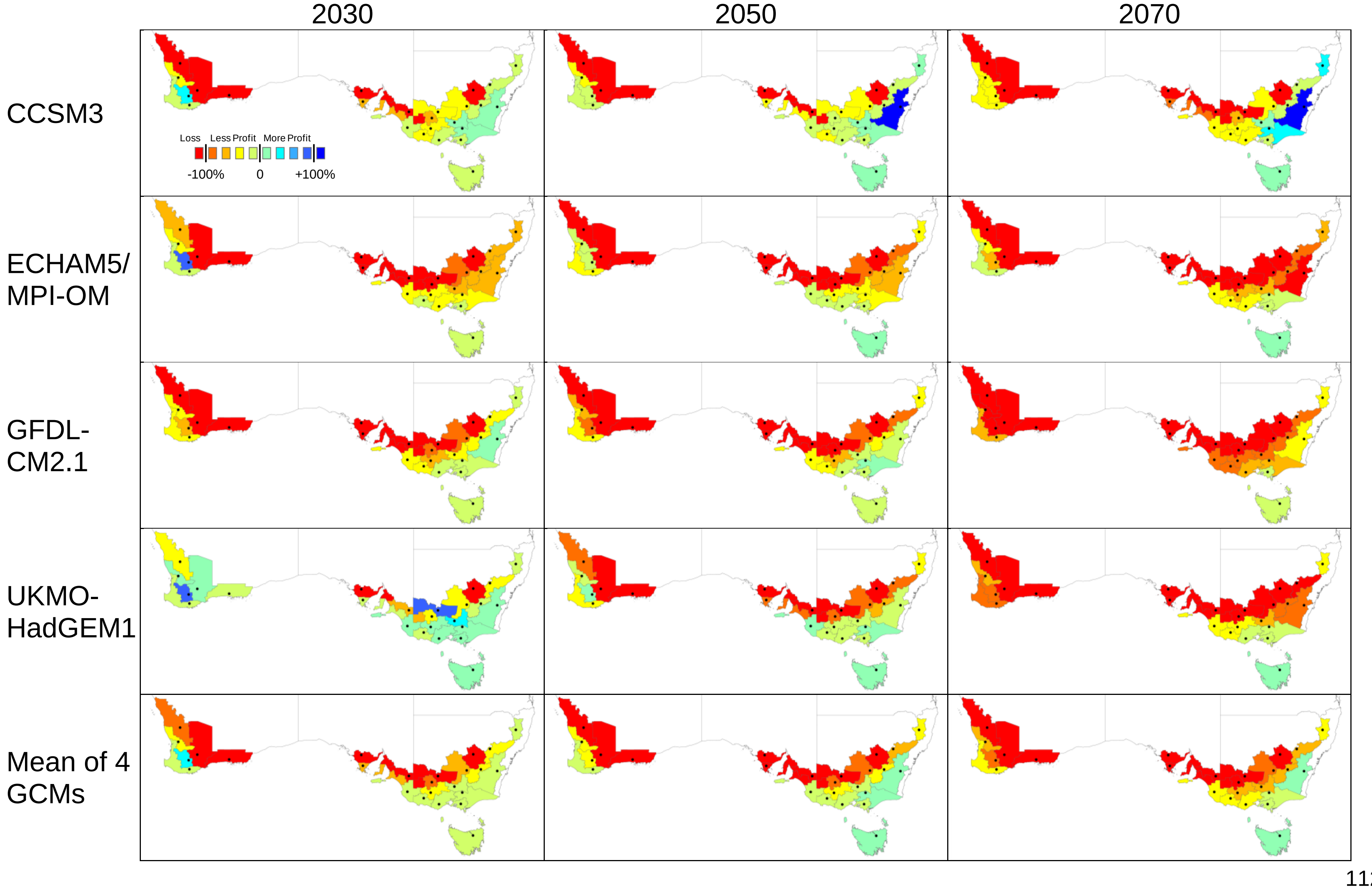


Table A7.3. Modelled changes in rainfall capture efficiency (transpiration per unit of rainfall), transpiration efficiency (ANPP per unit of transpiration), pasture utilization rate and conversion efficiency ($income/tonne pasture DM consumed) for each of 5 livestock enterprises at 2030, 2050 and 2070. Values are averages across 25 regions in southern Australia (area-weighted) and 4 GCM projections.

		Rainfall Capture Efficiency (mm/mm)	Transpiration Efficiency (kg/ha.mm)	Utilization rate (kg/kg)	Conversion Efficiency ($/kg)	Income per Unit Rainfall ($/ha.mm)
Merino ewes	2030	-8%	-2%	-16%	+1%	-24%
	2050	-11%	-1%	-23%	0%	-32%
	2070	-14%	-3%	-31%	-0%	-42%
Crossbred ewes	2030	-8%	-3%	-15%	0%	-24%
	2050	-11%	-1%	-22%	-1%	-32%
	2070	-14%	-2%	-30%	-2%	-42%
Beef cows	2030	-9%	+6%	-10%	+1%	-13%
	2050	-12%	+12%	-14%	+1%	-14%
	2070	-17%	+15%	-20%	0%	-24%
Wethers	2030	-8%	-3%	-15%	+1%	-23%
	2050	-11%	-1%	-23%	+1%	-32%
	2070	-14%	-3%	-31%	0%	-42%
Steers	2030	-8%	-3%	-15%	0%	-24%
	2050	-11%	-1%	-22%	+1%	-31%
	2070	-14%	-3%	-32%	+1%	-42%

The most striking feature of Figure 7.7, however, is the set of 6 locations (Dalwallinu, Lake Grace, Esperance, Kyancutta, Lameroo and Birchip) where stocking rates and hence pasture consumption are reduced to negligible levels in a number of projected climates. For these combinations of location and projected climate, the ground cover constraint cannot be met even at minimal stocking rates, i.e. there is no feasible grazing system with the present-day feedbase.

Changes in the climate within each location had relatively little effect on the conversion of consumed pasture into product and hence income (Figure A7.8; Table A7.3). As a result, the changes in long-term average income and profit from Merino ewe enterprises shown in Figures A7.9 and A7.10 were driven by the amount of pasture that can be consumed without reducing ground cover below threshold levels. Owing to the compounding effects of both lower ANPP and lower utilization of the pasture grown, however, the proportional changes in income were generally below the proportional changes in ANPP. By 2050 Merino ewe production in most regions is predicted to produce substantially less income in most regions under at least 3 of the 4 GCM projections; under the climate projected by the most favourable GCM (CCSM3) the average reduction in annual income over all regions was 24% in 2050 and 23% in 2070, while for GFDL-CM2.1 the corresponding reductions in income were 44% and 57%.

When annual income changes under changed climates are compared between enterprises, the similarities are much stronger than the differences at the majority of locations (in Figure A7.11, the proportional changes in income are mostly close to the 1:1 line). At locations such as Mount Barker, Cummins and Cootamundra the relative changes in projected income are very similar across all five enterprises. In a second, larger group of locations that includes Bakers Hill, Lucindale, Launceston, Tatura and Goulburn, the relative declines in income in beef cow enterprises are smaller than in the other four enterprises. The third group of locations is the 6 locations where stocking rates are reduced to negligible levels in the majority of cases. Ellinbank and Narrandera are intermediate between the first and second groups, and Swan Hill is intermediate between the second and third group. The departures from a common response in livestock income across enterprises at Armidale were unique, with the wether enterprise performing relatively worse than the others and the beef cattle enterprise performing relatively better than the ewe enterprises under benign projected climates but relatively worse when income was projected to decline.

When averaged across all regions, the relative decline in income from beef cattle production was smaller than for the other 4 enterprises; the differences can be attributed to a combination of modest increases in transpiration efficiency and smaller declines in utilization rate in beef cow systems. The beef cow enterprises were generally among the least profitable enterprises at each location under historical climate, however, and there was no combination of location x projected climate where the beef cattle enterprise became the most profitable.

Implications

This modelling study has shown that, without doubt, rainfall outcomes will dominate the impacts of a changing climate on the functioning of livestock production systems in southern Australia (Figure A7.5). Other, more certain impacts (increasing CO_2 concentrations and temperatures) will have secondary effects. It is to be hoped, therefore, that the new round of GCM projections being prepared for the next Assessment Report of the IPCC will deliver smaller levels of uncertainty in their predictions of future rainfall in Australia's agricultural areas.

Because of its geographic coverage, this study has revealed that the greatest impact of changing climates on temperate pasture and livestock production is likely to be in the cereal-livestock zone, in particular at its dry margin (Figure A7.10). Previous modelling studies of the responses of temperate pastures to climate change (Cullen *et al.* 2009, Alcock *et al.* 2010, Moore 2011) have focussed almost exclusively on locations with annual rainfalls greater than 450mm. The likely overall impact of climate change on southern Australian livestock production has therefore been underestimated to date.

In most locations, the main limit to livestock production is the amount of forage that can be removed without causing too great a risk of soil erosion. As a result, the 5 enterprises modelled exhibited broadly similar production responses to each of the 12 projected climates. In locations where production declines over time, therefore, shifts in the economic attractiveness of enterprises will depend on their cost structures: those enterprises with a high ratio of costs to income will be the ones where a given proportional decline in income reduces profit the most.

It is important to understand that this analysis is an impacts study only, and should be read in conjunction with Appendix 8. A range of different adaptation options may ameliorate these climate change impacts. It appears, however, that the balance of risk is on the downside and that such adaptive management changes (or ways of increasing product prices relative to input costs) will need to be found and put into practice by livestock producers across southern Australia.

Figure A7.11(a). Comparison of modelled proportional change in long-term average annual income from 5 livestock enterprises (relative to the 1970-1999 base period) at 6 locations in Western Australia under 4 projected future climates based on the SRES A2 scenario. Income values for each enterprise x location x climate scenario are computed at optimal sustainable stocking rates. Symbols denote ■ CCSM3, ■ ECHAM5/ MPI-OM, ■ GFDL-CM2.1, ■ UKMO-HadGEM1; ◆ 2030, ■ 2050, ● 2070.

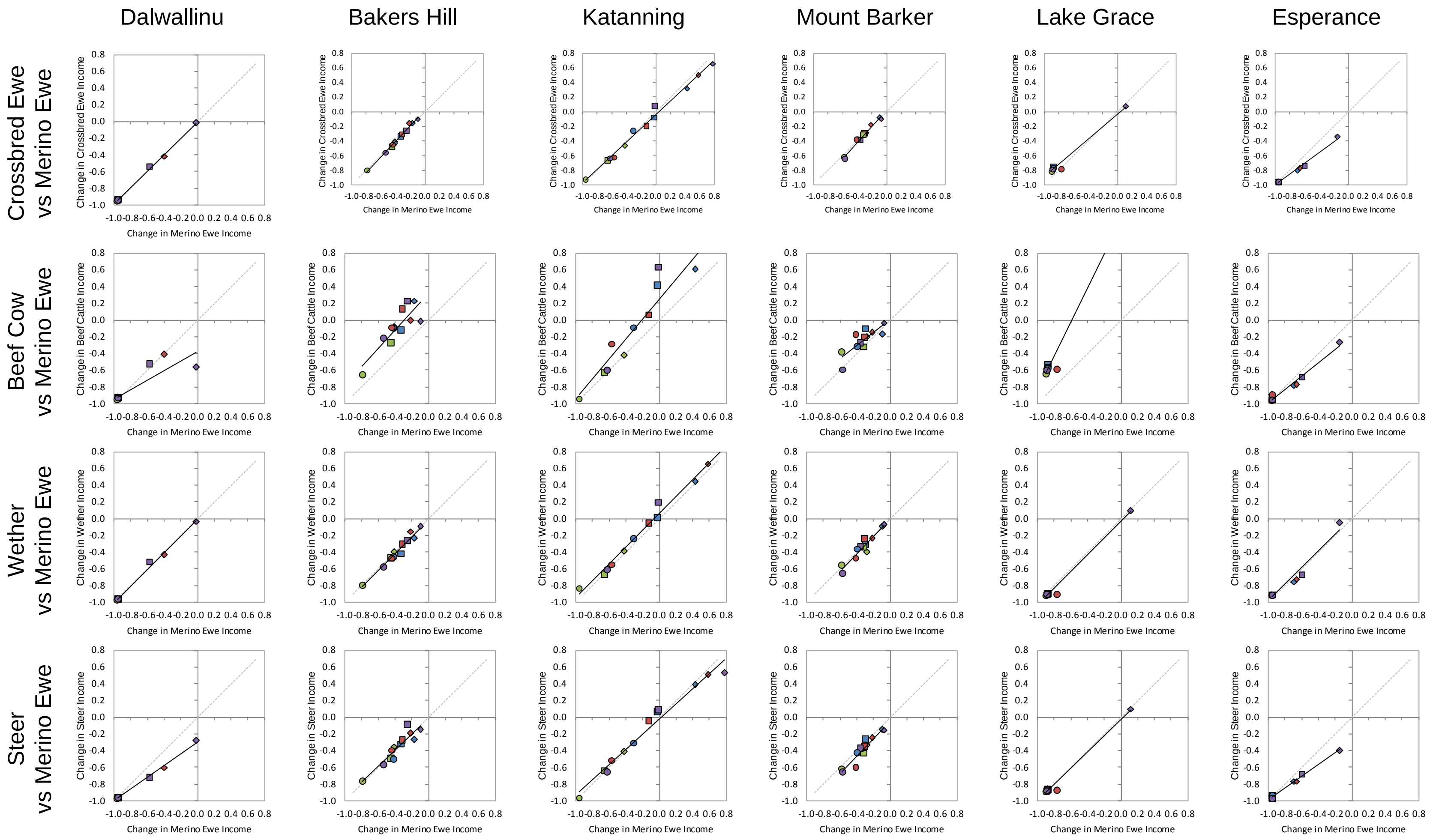


Figure A7.11(b). Comparison of modelled proportional change in long-term average annual income from 5 livestock enterprises (relative to the 1970-1999 base period) at 7 locations in South Australia and northern Victoria under 4 projected future climates based on the SRES A2 scenario. Income values for each enterprise x location x climate scenario are computed at optimal sustainable stocking rates. Symbols denote ■ CCSM3, ■ ECHAM5/ MPI-OM, ■ GFDL-CM2.1, ■ UKMO-HadGEM1; ◆ 2030, ■ 2050, ● 2070.

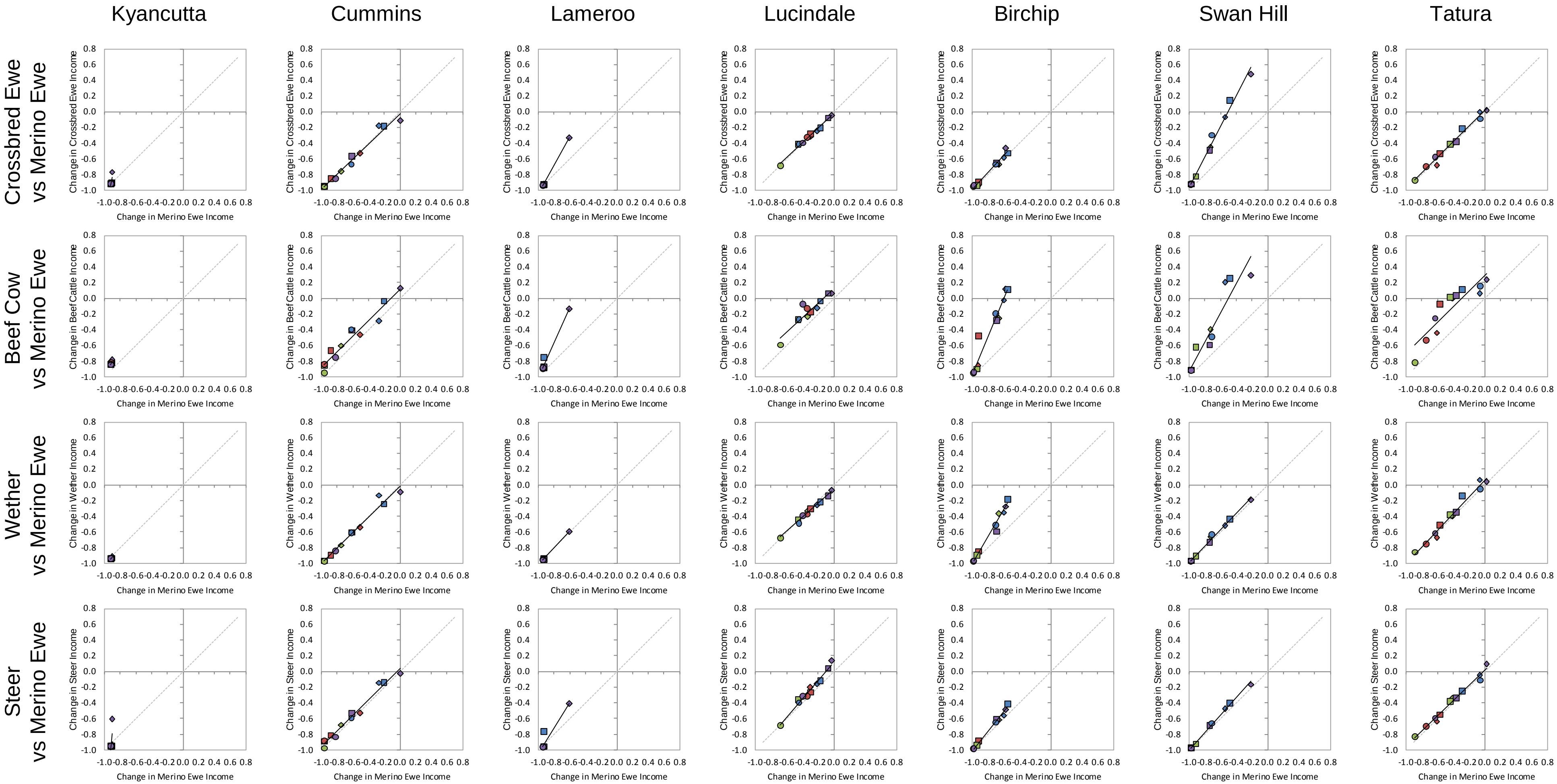


Figure A711(c). Comparison of modelled proportional change in long-term average annual income from 5 livestock enterprises (relative to the 1970-1999 base period) at 6 locations in southern Victoria, eastern Victoria and Tasmania under 4 projected future climates based on the SRES A2 scenario. Income values for each enterprise x location x climate scenario are computed at optimal sustainable stocking rates. Symbols denote ■ CCSM3, ■ ECHAM5/ MPI-OM, ■ GFDL-CM2.1, ■ UKMO-HadGEM1; ◆ 2030, ■ 2050, ● 2070.

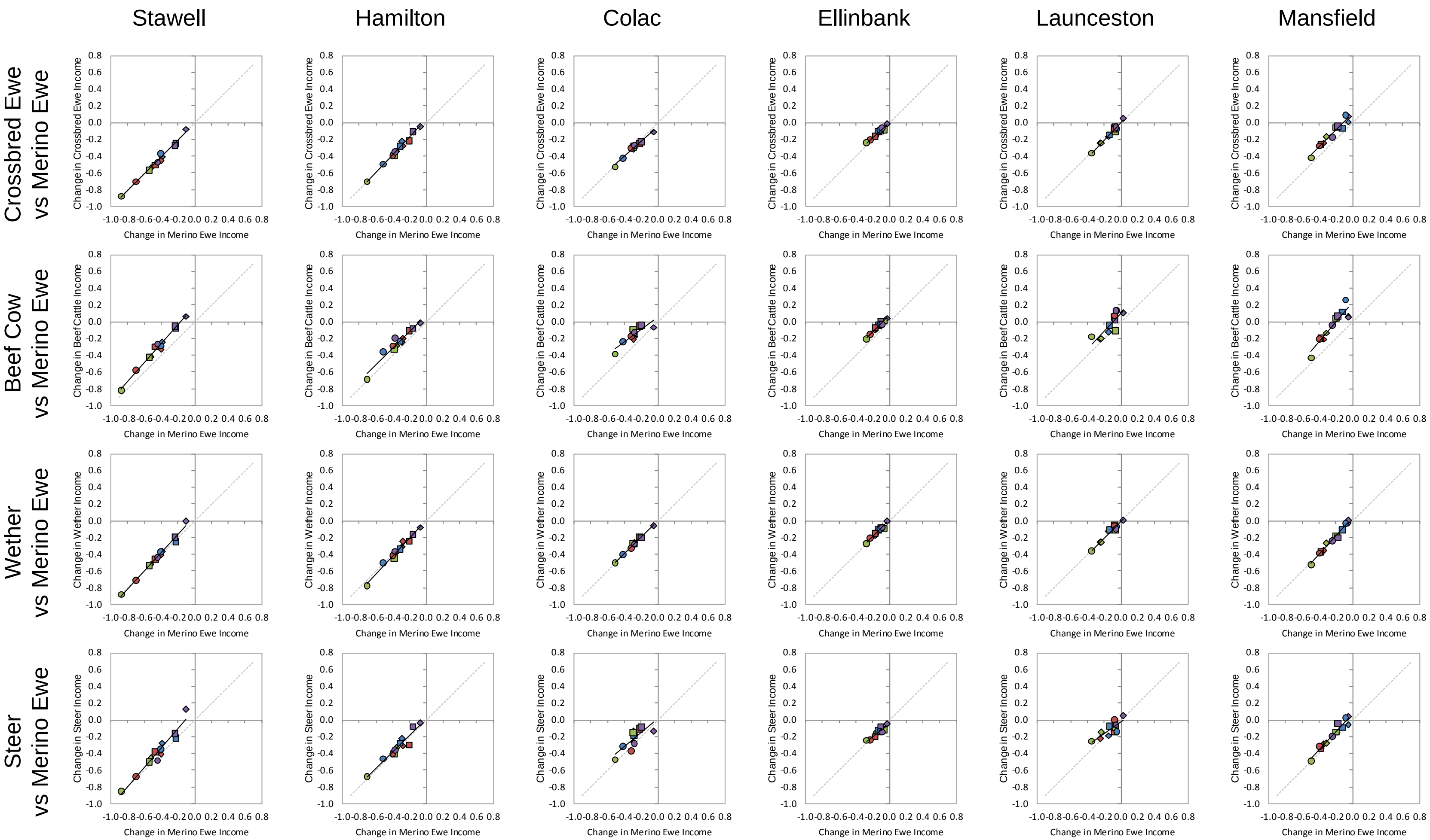
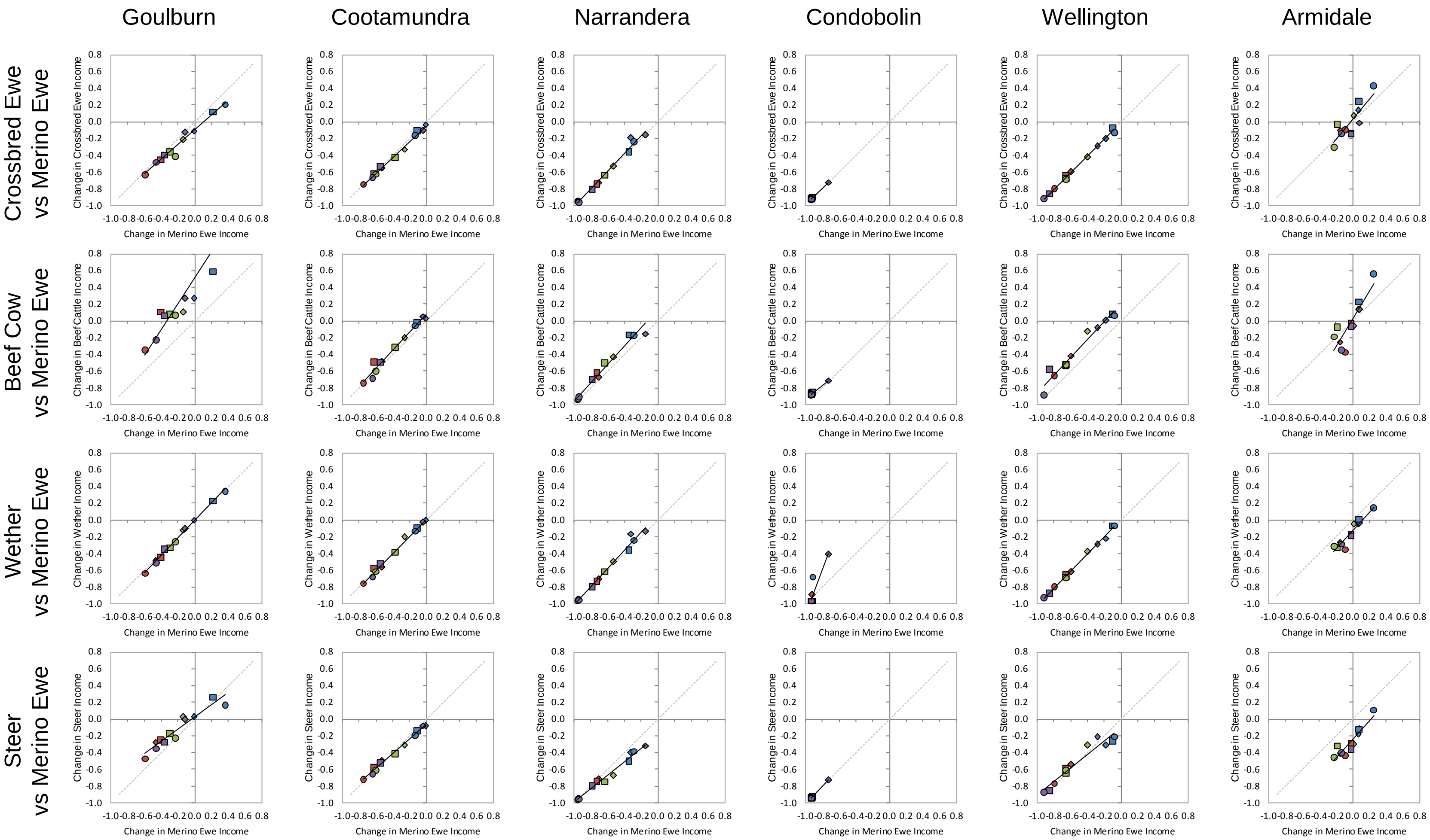


Figure A7.11(d). Comparison of modelled proportional change in long-term average annual income from 5 livestock enterprises (relative to the 1970-1999 base period) at 6 locations in New South Wales under 4 projected future climates based on the SRES A2 scenario. Income values for each enterprise x location x climate scenario are computed at optimal sustainable stocking rates. Symbols denote ■ CCSM3, ■ ECHAM5/ MPI-OM, ■ GFDL-CM2.1, ■ UKMO-HadGEM1; ◆ 2030, ■ 2050, ● 2070.



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Appendix 8. Adaptations to climate change across southern Australia in 2030, 2050 and 2070

Introduction

Previous modelling studies indicate that expected climate changes are likely to reduce the productivity of improved pastures at a number of locations in southern Australia (Appendix 1; Cullen et al. 2009), and that the stocking rates that can be sustained will decrease disproportionately owing to increased risk of low ground cover (Alcock et al. 2010). Simulation results in the current project (Appendix 7) have demonstrated that major declines in pasture and livestock production will be widespread across southern Australia under the climates projected by a number of GCMs. Management for improved ground cover and more efficient conversion of pasture growth into production are therefore likely to be required in order for southern Australian livestock producers to adapt to climate change.

In this study we investigate the potential for a range of management and genetic changes, singly and in combination, to enhance the profitability and sustainability of livestock production across southern Australia under projected future climates at 2030, 2050 and 2070. The GRAZPLAN modelling tools have been applied to evaluate potential effectiveness of adaptation strategies under future projected climate (under the SRES A2 scenario) on pasture and livestock production of 25 representative farms across Southern Australia carrying 5 different grazing enterprises.

Methods

Selection of adaptation options for analysis

A wide variety of livestock adaptation options have been suggested for sustainable pasture and livestock production, such as alterations to rotation of pastures; grazing times; timing of reproduction; forage and animal genetics; integration within mixed livestock/crop systems including using adapted forage crops; reassessing fertilizer applications; and supplementary feeding (Daepp et al. 2001, Adger et al. 2003, Batima et al. 2005, Howden et al. 2007). We have selected candidate adaptations based on their likely fit with future rainfall patterns (e.g. a greater proportion of rainfall during summer) and their capacity to either reduce the frequency of low ground cover or else to increase livestock conversion efficiency.

The options that we have examined are shown in Table A8.1.

- Increasing soil nutrient levels will increase plant growth and so should improve

Table A8.1. Adaptation options that were modelled at 25 locations and for each of the 5 livestock enterprises for which they were meaningful.

Feedbase adaptations	Genetic adaptations	Management adaptations
1. Higher soil fertility	4. Increased breed standard reference weight	8. Confinement feeding in summers with low pasture mass
2. Management to remove annual legumes, in order to slow the loss of ground cover	5. Increased wool production at constant standard reference weight	9. Altered stocking rate
3. Sowing a portion of land to lucerne pastures	6. Increased sire standard reference weight	
	7. Increased conception rate	

ground cover levels.

- Legume residues have weaker structure compared to grass species and so degrade more rapidly over summer; a shift in pasture composition toward legume dominance under climate change can therefore be expected to make soil erosion risk greater unless stocking rates are reduced to compensate. Managing pastures for lower legume content might therefore allow higher stocking rates in future climates, at the cost of reduced production per animal.
- Introducing summer-active pastures such as lucerne to the feedbase, or increasing the proportion of lucerne where it is already used, is potentially an attractive option because rainfall is expected to shift toward the summer season in future decades. There is also good evidence that increased atmospheric CO_2 concentrations are likely to favour legumes over grasses in temperate pastures (e.g. Clark *et al.* 1997).
- “Confinement feeding”, i.e. placing animals in a feedlot during summer and autumn when pasture mass is low, has been considered as an adaptation scenario to conserve ground cover.

A number of possible adaptations through improved livestock genetics were examined, on the premise that using animals with lower maintenance requirement or higher feed conversion efficiency would mitigate the consequences of a lower amount of consumable pasture growth. The options that we considered were:

- Increasing animal size. Maintenance energy requirements vary with the 0.75 power of body weight while intake increases roughly linearly. Larger animals should therefore use a smaller proportion of the energy in consumed forage for maintenance, leaving more energy for growth, wool production or reproduction. This genotypic attribute of an animal breed is represented in the GRAZPLAN ruminant model as the “standard reference weight” of a breed, i.e. the weight of a mature, empty female in average body condition.
- Increase in wool production at constant body size. This adaptation option implies a redirection of animals’ energy and protein intake toward wool production. It is represented in the model as the ratio of the “potential fleece weight” to the standard reference weight.
- Increased reproduction rate. Overall reproduction (marking) rate is the product of fertility (proportion of females falling pregnant), fecundity (number of offspring conceive per pregnant female) and the survival rates of foetuses and of newborn lambs or calves. In southern Australian livestock systems, the great majority of ewes and cows conceive each year and survival from conception to birth and of newborn calves is also high; the greatest scope for genetic improvement therefore lies in fecundity and in perinatal survival in sheep. We have focussed on fecundity as an adaptation option, as it would apply to both sheep and cattle enterprises. Most of any reproductive rate increase in both sheep and cattle will have to appear as an increase in the proportion of twins or triplets.
- Increase in sire body size relative to dam size. This option is limited to enterprises where terminal sires are used. It result in larger offspring and should increase the overall energetic efficiency of the system. However the usefulness of this change is limited by the risk of dystokia; if the foetus becomes too large, birth becomes difficult and the death rate of lambs or calves increases.

A key difference between genetic adaptations and the feedbase and livestock management adaptations is that the former need to be implemented slowly over time. In the other words, we needed to consider gradual improvement of genetic over time, using rates of progress that should be achievable given our knowledge of rates of genetic improvement during the last 20-30 years.

Modelling analyses

The GRAZPLAN grassland and animal simulation models (Moore *et al.* 1997, Freer *et al*.1997; www.csiro.au/grazplan), were applied as implemented in the GrassGro decision support tool (Moore *et al.* 1997), in order to simulate the potential effects of adaptations under future projected climate on pasture and livestock production. The models simulate four effects of increased CO_2 concentration: a direct CO_2 fertilization effect, reduced transpiration due to partial stomatal closure, decreased specific leaf area, and decreased leaf nitrogen content. A range of effects of changes in soil moisture and temperature are also covered by the models.

The same set of 25 locations was used as for the impacts study described in Appendix 7; details can be found in Appendix 11. At each location, 5 grazing enterprises (self-replacing Merino ewes, crossbred ewes, self-replacing Angus beef cattle, Angus steers and Merino wethers) were modelled. Within each enterprise, the same livestock genotypes, prices for livestock and wool and variable costs of production were assumed across all locations in order to facilitate comparisons across sites. Management policies (livestock replacement, the timing of the reproductive cycle, the sale of young stock and thresholds for supplementary feeding) were described separately for each enterprise x location combination. A “historical” scenario was simulated over the years 1970-1999 as a reference period. Climates projected by 4 GCMs (CCSM3, ECHAM5/MPI-OM, GFDL-CM2.1 and HadGEM1) under the SRES A2 scenario at 2030, 2050 and 2070 were downscaled into daily weather data sequences using a technique adapted from that of Zhang (2007). CO_2 concentrations of 350 p.p.m for historical climate and 451, 532 and 635 p.p.m at 2030, 2050 and 2070 were assumed. A factorial simulation experiment was conducted in which the factors were climate scenario and date (1 + 4 x 3 levels), location (25), livestock enterprise (5), adaptation strategy and stocking rate.

For each combination, a range of 9-15 stocking rates was modelled. Physical and financial outputs from the grazing system were stored from each simulation run. A long-term rate of operating profit/income was calculated as the gross margin less overhead costs, an operator allowance and a further adjustment for the capital cost of the livestock required at each stocking rate with a 7% interest rate. An optimal sustainable stocking rate was selected as that which gave highest profit while keeping the frequency of low ground cover (cover < 0.70) below a location-specific threshold; all results are reported at this stocking rate.

Otherwise, the climate change adaptations described above were incorporated into the GRAZPLAN models as follows:

Higher soil fertility	The “fertility scalar” in each modelled paddock was increased to reflect an overall increase in soil fertility. The initial values of the fertility scalar varied from location to location in line with local practice; fertility scalars were increased by 0.1 units (on a 0-1 scale) up to a maximum of 0.95. At some locations, a further increase in fertility scalars (usually in low-fertility native pastures) was also examined.
Management to remove annual legumes	The pasture in each modelled paddock was modified to remove either all annual legumes other than lucerne (including white clover at Ellinbank) or else all legumes including lucerne.
Sowing a portion of land to lucerne	Either 20% or 40% of land from the most-productive soil class was separated into an extra paddock that contained a

pastures	pure lucerne pasture. Where the pastures at a location already included a lucerne component (for example at Wellington), this new lucerne paddock was in addition to the existing lucerne. Rooting depths of the lucerne pasture were set to be somewhat deeper than that of grasses.
Increased breed standard reference weight (SRW)	The breed standard reference weight and (where relevant) the potential fleece weight and sire standard reference weight were adjusted upward to reflect increases of 0.5% per year starting in 2010, i.e. a 10% increase in 2030, a 20% increase in 2050 and a 30% increase in 2070. As in the impacts study, the same genotype was used for each enterprise x date at all locations.
Increased wool production at constant SRW	The potential fleece weight of sheep breed was adjusted upward to reflect increases of 0.5% per year starting in 2010. The same genotype was used for each enterprise x date at all locations.
Increased sire SRW	This adaptation was only applied to the crossbred ewe enterprise, as the other breeding enterprises assumed self-replacing flocks and herds in which sire and dam genotypes were the same. The standard reference weight of rams was adjusted upward to reflect increases of 0.5% per year starting in 2010. The same genotype was used for each date at all locations.
Increased conception rate	The underlying genetic parameters governing conception rate in the GRAZPLAN model were adjusted so as to give conception rates (averaged across locations) that increased by 0.005 lambs/ewe/year in the Merino ewe enterprise, 0.0075 lambs/ewe/year in the crossbred ewe enterprise and 0.0025 calves/cow/year in the beef cow enterprise. These parameters were then applied at each location, in combination with system-specific mating dates, to derive reference conception rates for each location x enterprise x date.
Confinement feeding in summers with low pasture mass	A supplementary feeding rule was introduced to each grazing system in which all livestock were removed from pastures and fed a maintenance ration in a feedlot whenever total pasture mass fell below either 2000, 1500 or 1000 kg/ha. Animals were returned to grazing when total green herbage mass exceeded 500 kg/ha. All three threshold biomasses for livestock removal were trialled for each location x enterprise x date combination.

Adaptations were evaluated in terms of their “relative effectiveness”, computed as:

$$\text{Relative Effectiveness} = \frac{(\text{Total income with adaptation}) - (\text{Total income without adaptation})}{(\text{Historical total income}) - (\text{Total income without adaptation})}$$

By examining the effectiveness of adaptations in terms of income rather than profit, we are taking an “industry” view of adaptation; a “producer” view would focus more on profitability.

Combinations of adaptation strategies were also examined, because a single option may not be able to recover all declines in productivity of the pasture and livestock system. With 8 distinct adaptation types (plus stocking rate), there were at least 255 different combinations that could have been evaluated; the limited available computing resources meant that only a subset of these possibilities could be examined. A small set of combinations of adaptations was modelled for every location x enterprise x date; these combinations were selected to concentrate on adaptations with high relative effectiveness in recovering the impact of climate change on the total value of livestock production across southern Australia. In addition, a single “locally-relevant” combination of adaptations was selected for each location x enterprise combination by (i) computing the average relative effectiveness of each adaptation option over the years 2030, 2050 and 2070, (ii) selecting higher fertility if its average relative effectiveness was positive, (iii) adding the genetic adaptation with highest average relative effectiveness if this was positive, and (iv) adding the most effective of the remaining 3 adaptations if it also had a positive average relative effectiveness.

Results

Single climate change adaptations at 2030, 2050 and 2070

Significant increases in operating profit were estimated under the higher fertility adaptation strategy relative to with no adaptation at most of the 25 locations, with the result that its overall relative effectiveness was high (Table A8.2). Adding lucerne to the feedbase (generally at 40% of land area) had the second largest effect overall (Table A8.2), with increased conception rate in third place. The “zero legume” adaptation, on the other hand, was estimated to have little positive effect. This suggests that even under future climates, the higher nutritive value of legumes outweighs the disadvantage of more rapid ground cover loss. The results for this adaptation varied widely between locations, GCMs and future dates, however; for example, legume removal was estimated to have a relative effectiveness of 0.80 at Cummins in 2030. Adaptations that increased meat production had a larger overall relative effectiveness than increasing wool production at constant body size; this result is consistent with the current relative values of wool and meat production in southern Australia.

The relative effectiveness of the feedbase-related adaptations and of confinement feeding decreased over time from 2030 to 2070 (Table A8.1). For the genetic adaptations, there was a tendency for relative effectiveness to increase from 2030 to 2050 and then to stabilize between 2050 and 2070.

Figures A8.1 to A8.3 expand on Table A8.1 by showing the range of relative changes in income ($/ha) of the different adaptation options across the 25 locations, for each combination of enterprise and date. Again, higher soil fertility had the highest positive

Table A8.2. Relative effectiveness of a range of different potential adaptations in recovering the impact of climate change on the total value of livestock production across southern Australia (0.0 = no benefit; 1.0 = a return to the 1970-99 baseline value of production). Adaptations were only applied to location x enterprise combinations where they increased profit at the sustainable optimum stocking rate. Values are averages over 4 GCMs and value-weighted averages over 25 locations and 5 livestock enterprises.

	2030	2050	2070
Higher soil fertility	0.62	0.67	0.44
Add lucerne to the feedbase	0.45	0.50	0.41
Increased conception rate	0.15	0.32	0.31
Increased livestock size	0.11	0.27	0.28
Confinement feeding	0.22	0.26	0.18
Increased ram size	0.07	0.16	0.16
Increased fleece weight	0.03	0.06	0.05
No annual legumes	0.01	0.01	0.01

Figure A8 1. Boxplots showing the relative change of income/ha at the optimal sustainable stocking rate from the historical baseline at 2030 for five livestock enterprises, for grazing systems in which a range of climate change adaptation options have been implemented. Each boxplot shows the distribution of income changes across 25 locations, after averaging over the climates predicted by 4 GCMs. Unlike Table A8.1, this figure shows the results of each adaptation when it is implemented, regardless of whether or not it is effective in recovering profitability. A value of 0 means that average income/ha is the same as for the historical period. N.A = no adaptation, F = increased soil fertility, C.F.1000 = 1000kg/ha confinement feeding, C.F.1500 = 1500kg/ha confinement feeding, C.F.2000 = 2000kg/ha confinement feeding, Z.L = Zero legume, L.20% = 20% lucerne, L.40% = 40% lucerne, I.B.S = increased body size, H.C.R = higher conception rate, I.P.F.W = increased potential fleece weight, S.R.W = increased standard reference weight

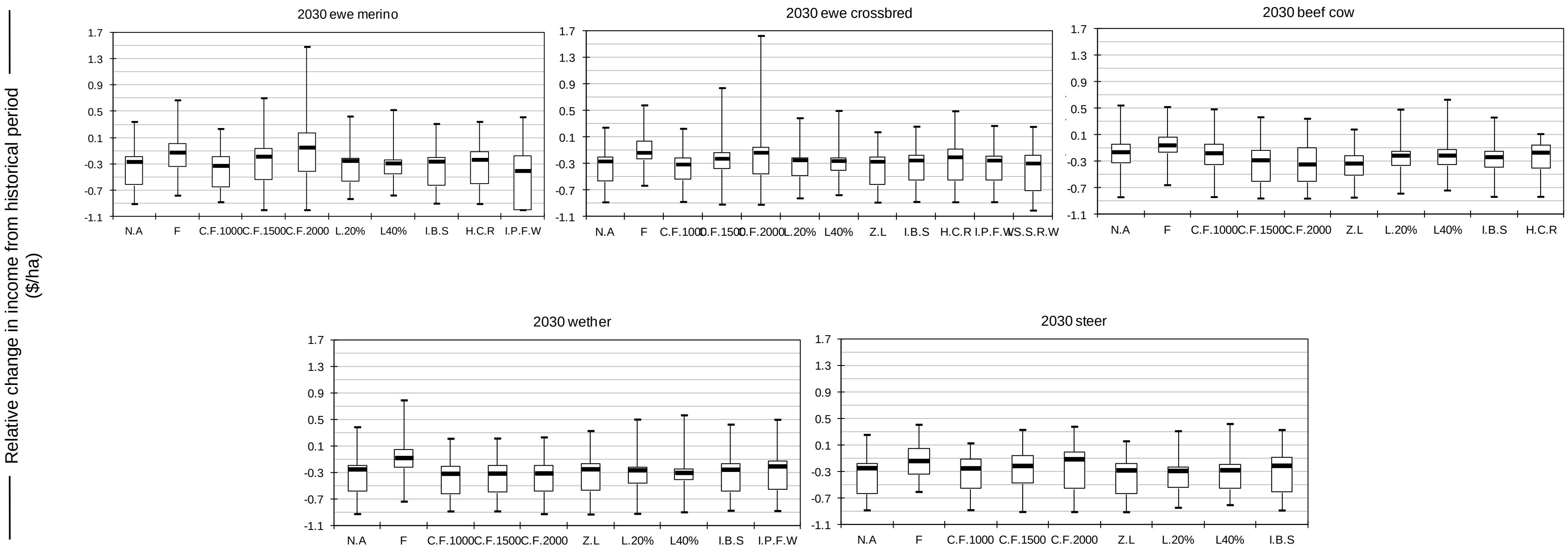


Figure A8 2. Boxplots showing the relative change of income/ha at the optimal sustainable stocking rate from the historical baseline at 2050 for five livestock enterprises, for grazing systems in which a range of climate change adaptation options have been implemented. Each boxplot shows the distribution of income changes across 25 locations, after averaging over the climates predicted by 4 GCMs. Presentation is as in Figure A8.2.

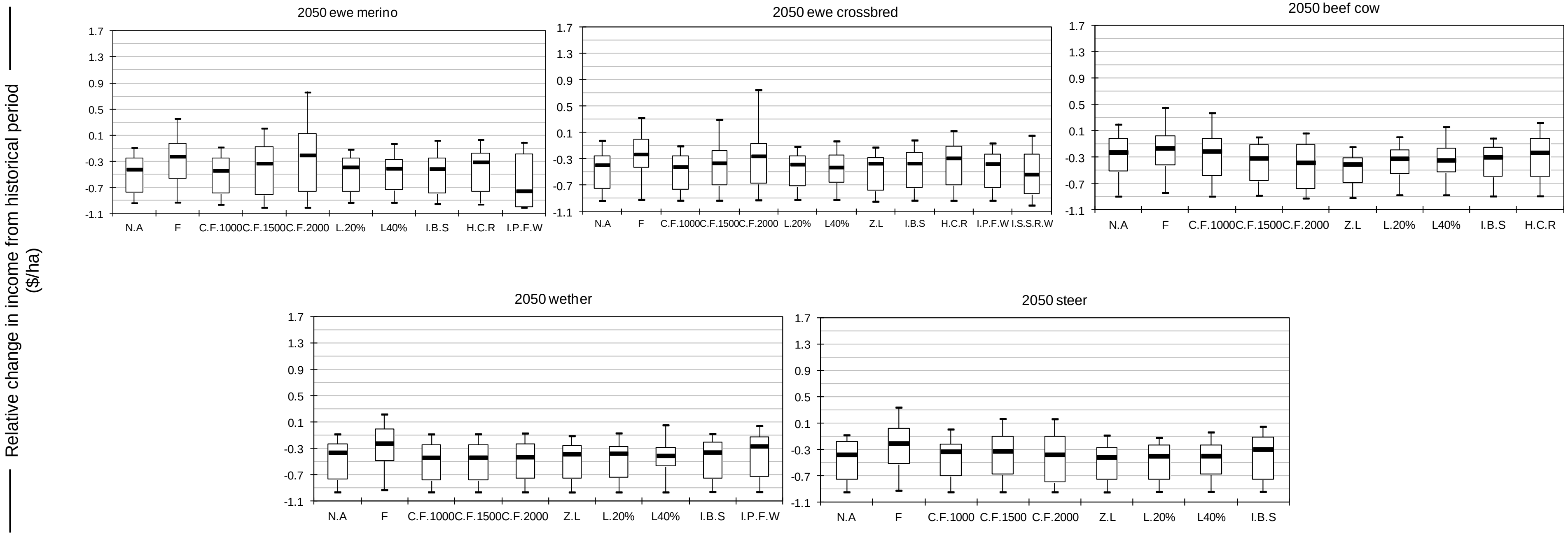
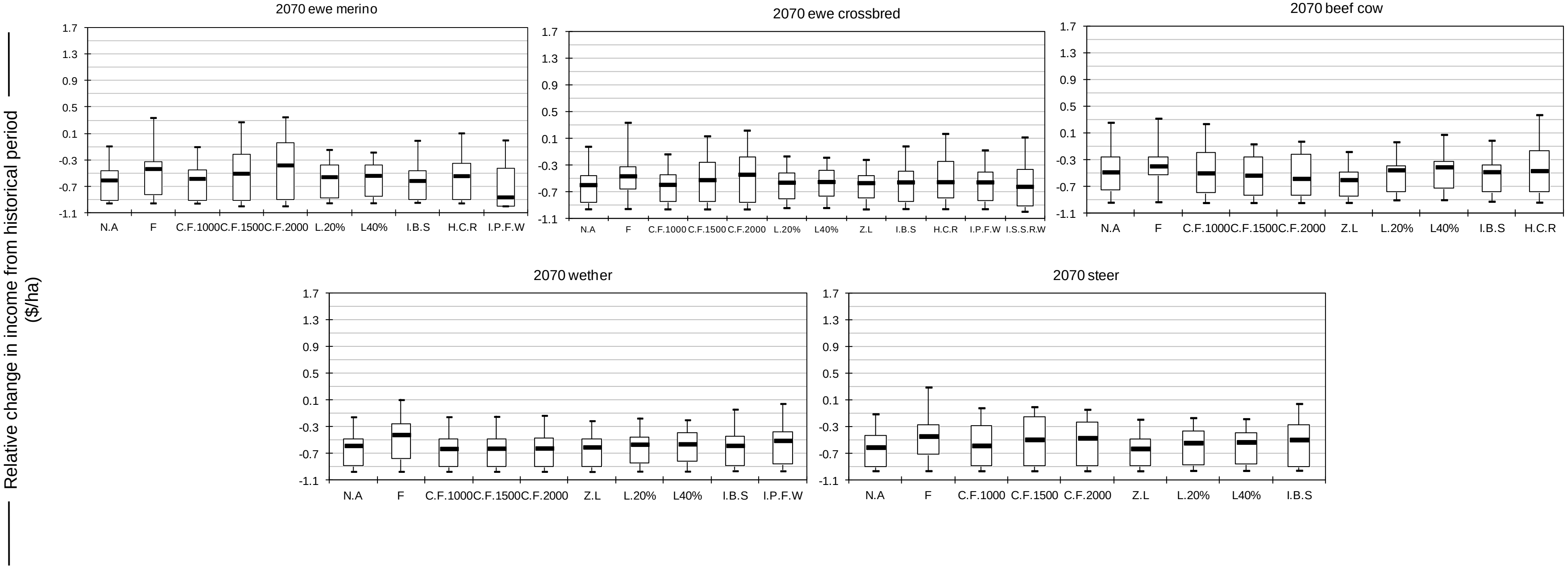


Figure A8.3. Boxplots showing the relative change of income/ha at the optimal sustainable stocking rate from the historical baseline at 2070 for five livestock enterprises, for grazing systems in which a range of climate change adaptation options have been implemented. Each boxplot shows the distribution of income changes across 25 locations, after averaging over the climates predicted by 4 GCMs. Presentation is as in Figure A8.2.

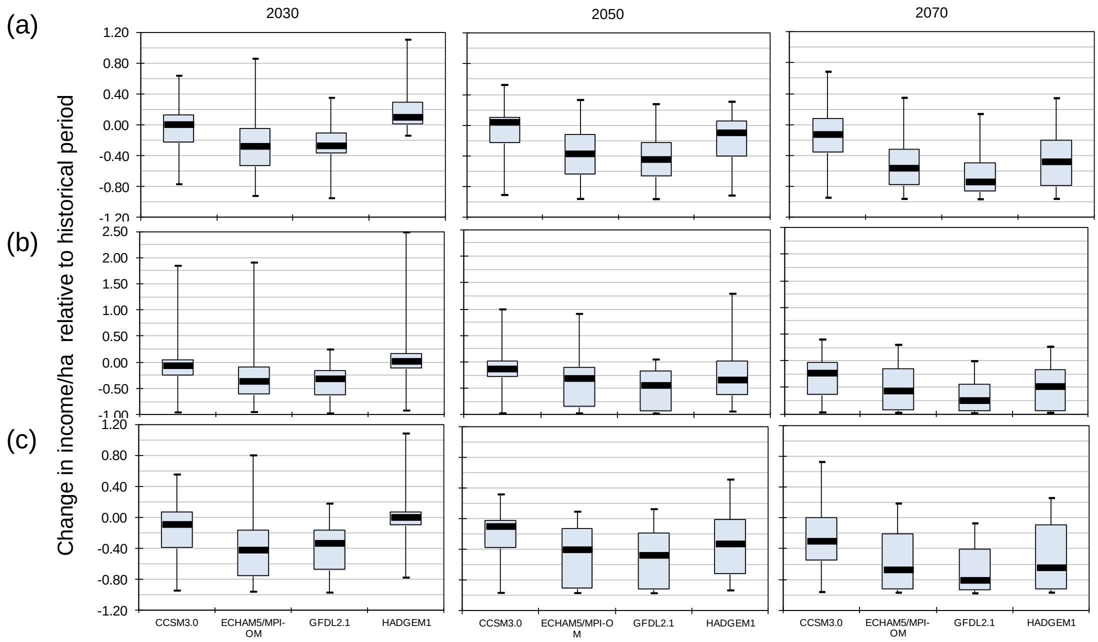


effect in recovering climate-change-induced declines in income. Under average of all GCMs, the smallest variation and consequently the smallest uncertainty of income recovered by fertility was modelled for beef cow enterprises at 2030. Confinement feeding with a threshold for confinement of 2000 kg/ha introduced greater variability between locations, particularly for the two ewe enterprises, but this variation decreased at 2070. The standard deviation across locations of the relative change in income increased from 2030 to 2050 and then deceased at 2070 in the no adaptation case, and this pattern was also followed when the following adaptations were implemented: adding 20% of lucerne to the feedbase, increased body size, increased ram size, increased fleece weight, and confinement feeding with a 1000 kg/ha threshold. For the higher conception rate adaptation, the standard deviation between locations increased sharply from 2030 to 2070, indicating that the effectiveness of this adaptation was diverging over time across locations. The pattern of response was the same but smaller for higher soil fertility. The standard deviation between locations of change in income decreased from 2030 to 2070 for three of the adaptation options (zero legume, adding 40% of lucerne to the feedbase and confinement feeding with a 1000 kg/ha threshold), indicating that the effectiveness of this adaptation was converging over time across locations.

Effectiveness of adaptations: uncertainty under different GCMs

Adaptation effectiveness differed widely among GCMs, presenting a challenge to our ability to estimate climate change impact and adaptation capacities. However, as shown in Figure A8.4 for changes in income in ewe crossbred enterprises, the differences between locations within a specific GCM are much greater than the differences in average response between GCMs. Overall the rank order of the impact of climate change projected by different GCMs was little altered by implementing single GCMs: income was reduced most under climates projected by GFDL2.1, then ECHAM5/MPI-OM and HadGEM1 with the smallest impacts estimated for climates projected by CCSM3.0. The exception was HADGEM1: its relative ranking changed from 2030 to 2070 as the climate conditions it projected became increasingly severe (Figure A8.4).

Figure A8.4. Variation of relative income change ($/ha) for ewe crossbred enterprises across Southern Australia under four GCMs at 2030, 2050 and 2070 after implementation of three climate change adaptation options Each boxplot shows the distribution of income changes across 25 locations. (a) higher soil fertility, (b) confinement feeding (2000 kg/ha threshold, note different scale), (c) higher conception rate.



Relative effectiveness of single adaptations over locations and time

Table A8.3 and Figure A8.5 show that when averaged over the four GCMs, in ewe crossbred enterprises, higher soil fertility and increased conception rate had the highest calculated relative effectiveness in areas with high rainfall; adding lucerne to the feedbase had the highest relative effectiveness in areas with lower rainfall. Increasing body size or fleece weight, were, in general, effective in drier areas. Locations where confinement feeding or increased ram size were effective were scattered across Southern Australia (Figure A8.5). Increased ram size was most effective at Launceston and its positive effect increased over time. Removing annual legume had the lowest overall effectiveness and was only effective at a few locations. (Figure A8.5). It should be noted, however, that the values shown in Table A8.3 and Figure A8.5 are averages over four GCMs; the effectiveness of adaptation options differed between GCMs (Figure A8.4).

Table A8.3. Relative effectiveness of a range of different potential adaptations in recovering the impact of climate change on the total value of livestock production at 25 locations across southern Australia (0.0 = no benefit; 1.0 = a return to the 1970-99 baseline value of production). For this table, adaptations were applied whether or not they increased profit at the sustainable optimum stocking rate. Values are averages over 4 GCMs. Where different levels of an adaptation were trialled, the best option has been selected for each location.

	Higher soil fertility			Increased conception rate			Add lucerne to the feedbase			Increased body size		
	2030	2050	2070	2030	2030	2050	2070	2050	2070	2030	2050	2070
Western Australia												
Dalwallinu	0.26	0.12	0.00	0.05	0.04	0.02	0.01	0.04	0.00	0.16	0.06	-0.01
Bakers Hill	0.73	0.37	0.17	0.45	0.16	0.12	0.07	0.38	0.15	0.49	0.46	0.27
Lake Grace	0.29	0.01	0.01	0.00	0.00	0.03	0.04	0.01	0.02	0.34	0.01	0.00
Katanning	-1.35	1.63	0.30	-0.99	-0.06	0.25	0.04	0.59	-0.01	-5.53	4.45	0.78
Esperance	0.35	0.07	0.00	0.22	0.01	0.02	0.00	0.00	0.00	0.19	0.07	0.00
Mount Barker	0.33	0.10	0.12	0.58	0.21	0.14	0.12	0.51	0.33	1.58	0.93	0.66
South Australia												
Kyancutta	0.29	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.04	-0.01	-0.01
Cummins	0.93	0.56	0.43	0.38	0.04	0.03	0.02	0.17	0.07	0.44	0.21	0.06
Lucindale	1.16	1.01	0.44	1.20	0.11	0.12	0.13	1.37	0.75	1.48	1.57	0.81
Lameroo	0.71	0.69	0.28	0.02	0.01	0.01	0.01	0.00	0.00	0.07	0.01	0.00
Victoria												
Birchip	0.72	0.58	0.34	0.13	0.03	0.01	-0.01	0.07	0.01	0.20	0.10	0.00
Colac	0.27	0.26	0.14	0.31	0.10	0.24	0.15	0.56	0.37	1.15	1.12	0.64
Stawell	0.40	0.42	0.22	0.17	0.03	0.06	0.07	0.27	0.07	0.64	0.55	0.26
Swan Hill	1.04	0.61	0.11	0.54	-0.01	0.02	0.03	0.08	-0.01	-0.09	-0.04	-0.02
Tatura	0.57	0.52	0.28	0.27	0.09	0.12	0.01	0.42	0.25	0.61	0.57	0.22
Mansfield	2.38	2.83	1.66	1.26	0.39	0.72	0.42	1.82	0.90	0.69	0.23	0.45
Hamilton	0.40	0.33	0.12	0.38	0.13	0.21	0.13	0.55	0.40	0.73	0.89	0.39
New South Wales												
Armidale	-8.29	20.02	13.59	-0.54	3.08	0.38	0.20	8.52	6.51	7.05	10.67	-8.53
Condobolin	0.43	0.10	0.40	0.05	0.01	0.01	0.01	0.00	0.00	-0.01	0.00	0.00
Cootamundra	0.75	0.40	0.25	-0.06	0.09	0.06	0.07	0.02	-0.01	0.53	0.34	0.15
Goulburn	1.43	1.20	0.73	0.51	0.14	0.20	0.32	0.54	0.57	0.46	0.48	0.31
Narrandera	0.40	0.23	0.14	0.07	0.03	0.03	0.03	0.12	0.02	0.33	0.19	0.03
Wellington	0.52	0.24	0.23	0.28	0.05	0.03	0.06	0.09	0.13	0.19	0.06	0.08
Tasmania												
Launceston	1.59	2.73	1.92	0.72	0.18	0.47	0.48	1.90	2.17	1.27	2.28	2.52

Table A8.3 *continued*

	Confinement feeding			Increased ram size			Increased fleece weight			No annual legumes		
	2030	2050	2070	2030	2050	2070	2030	2050	2070	2030	2050	2070
Western Australia												
Dalwallinu	0.11	0.05	0.00	0.01	0.01	0.00	0.02	0.01	0.00	-0.07	-0.04	0.00
Bakers Hill	-0.03	-0.02	0.02	-3.87	-1.86	-0.77	0.08	0.08	0.06	0.07	-0.01	0.04
Lake Grace	0.44	0.06	0.04	-0.02	0.02	0.02	0.03	0.01	0.02	-0.18	-0.01	-0.01
Katanning	-1.01	0.88	0.32	-0.05	0.24	-0.01	-0.10	0.19	0.08	0.27	-0.28	-0.04
Esperance	0.53	0.28	0.13	0.01	0.02	0.00	0.01	0.00	0.00	-0.02	-0.01	0.00
Mount Barker	0.52	0.36	0.29	0.43	0.41	0.39	0.09	0.07	0.00	-0.06	-0.03	0.07
South Australia												
Kyancutta	0.12	0.02	0.01	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00
Cummins	0.38	0.12	0.12	0.01	-0.01	0.01	0.06	0.02	0.02	0.55	0.24	0.14
Lucindale	0.22	0.16	0.16	0.46	0.69	0.43	0.07	0.09	0.11	-0.31	-0.28	-0.17
Lameroo	0.11	0.27	0.01	0.00	0.00	0.00	0.01	0.00	0.00	-0.13	-0.01	-0.01
Victoria												
Birchip	-0.02	0.08	-0.02	-0.14	0.08	0.01	0.01	0.01	-0.02	-0.09	-0.04	-0.02
Colac	0.19	0.15	0.04	0.03	0.10	0.05	0.05	0.16	0.12	0.11	0.08	0.05
Stawell	-0.07	-0.07	0.00	0.09	0.17	0.04	0.04	0.09	0.07	0.07	0.01	-0.01
Swan Hill	0.31	0.20	0.07	0.29	-0.01	-0.05	0.08	0.04	0.00	-0.15	-0.10	-0.02
Tatura	0.10	0.06	0.03	0.30	0.35	0.15	0.05	0.05	0.06	0.02	0.06	-0.01
Mansfield	-0.52	-0.45	-0.10	0.91	1.51	0.56	0.33	0.40	0.37	-0.18	-0.12	-0.21
Hamilton	0.01	0.03	0.10	0.05	0.10	0.06	0.08	0.15	0.06	0.08	0.01	0.04
New South Wales												
Armidale	9.76	-13.25	-11.00	40.44	-56.57	-36.84	5.67	-4.85	-4.13	9.97	-15.25	-11.14
Condobolin	0.12	0.00	0.08	0.00	0.00	0.01	0.00	0.00	0.01	0.02	-0.01	-0.01
Cootamundra	0.13	0.12	0.16	0.04	0.01	0.04	0.07	0.03	0.04	0.05	0.03	0.02
Goulburn	-0.08	-0.06	-0.01	0.06	0.06	0.13	0.11	0.11	0.22	-0.05	-0.05	-0.09
Narrandera	0.02	0.09	0.08	0.04	0.08	0.00	0.04	0.02	0.03	-0.07	0.04	0.01
Wellington	0.27	0.16	0.17	0.24	0.05	0.05	0.04	0.04	0.04	0.65	0.46	0.50
Tasmania												
Launceston	-0.38	-0.56	-0.21	0.59	1.64	1.80	0.10	0.39	0.43	0.00	-0.52	-0.57

Figure A8.5. Relative effectiveness of single adaptations in recovering the impact of climate change on total income from crossbred ewe production at 25 locations across southern Australia (0.0 = no benefit; 1.0 = a return to the 1970-99 baseline value of production). Adaptations were applied whether or not they increased profit at the sustainable optimum stocking rate. Values are averages over 4 GCMs. Where different levels of an adaptation were trialled, the best option has been selected for each location.

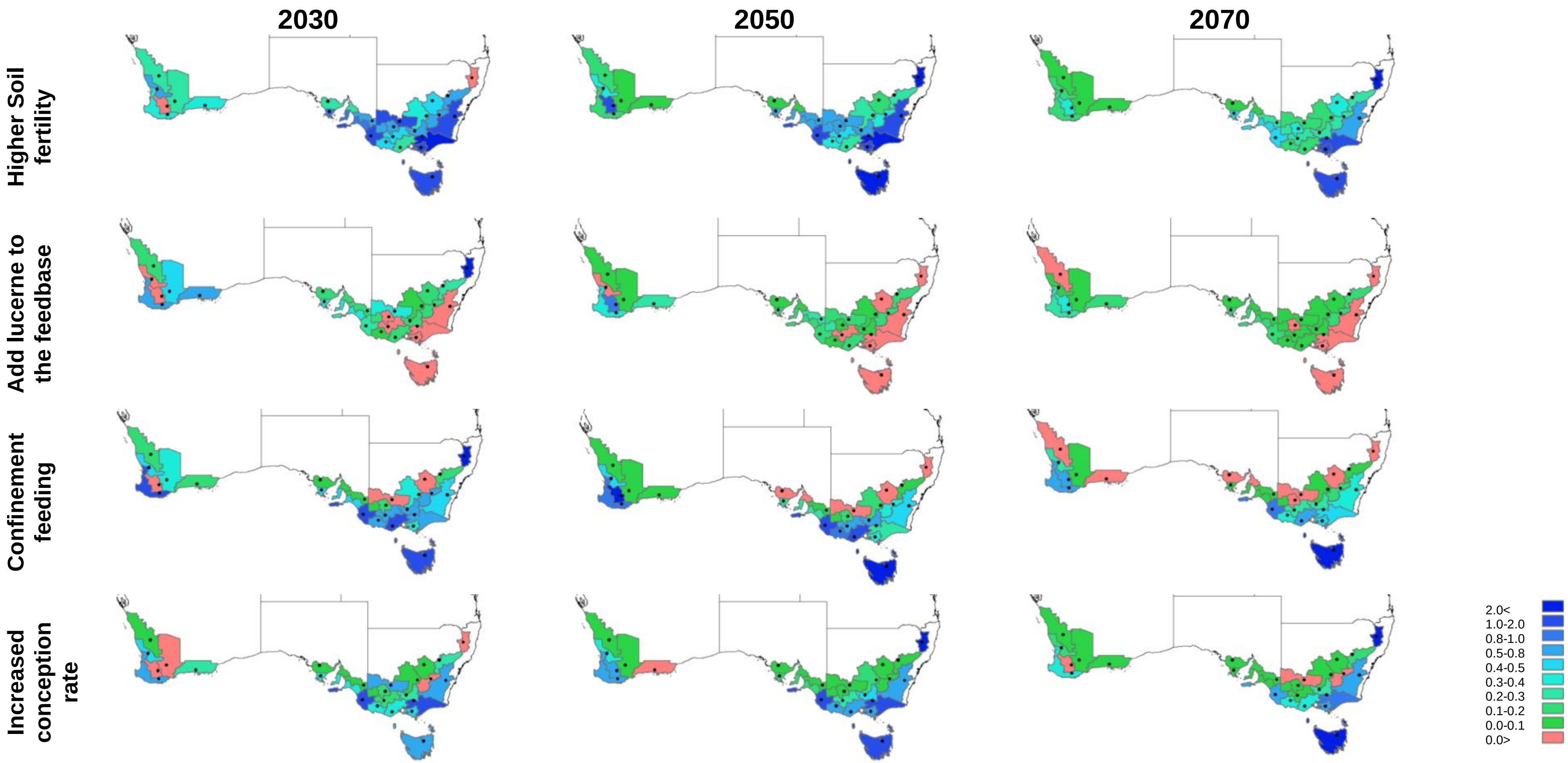


Figure 8.5 *continued*

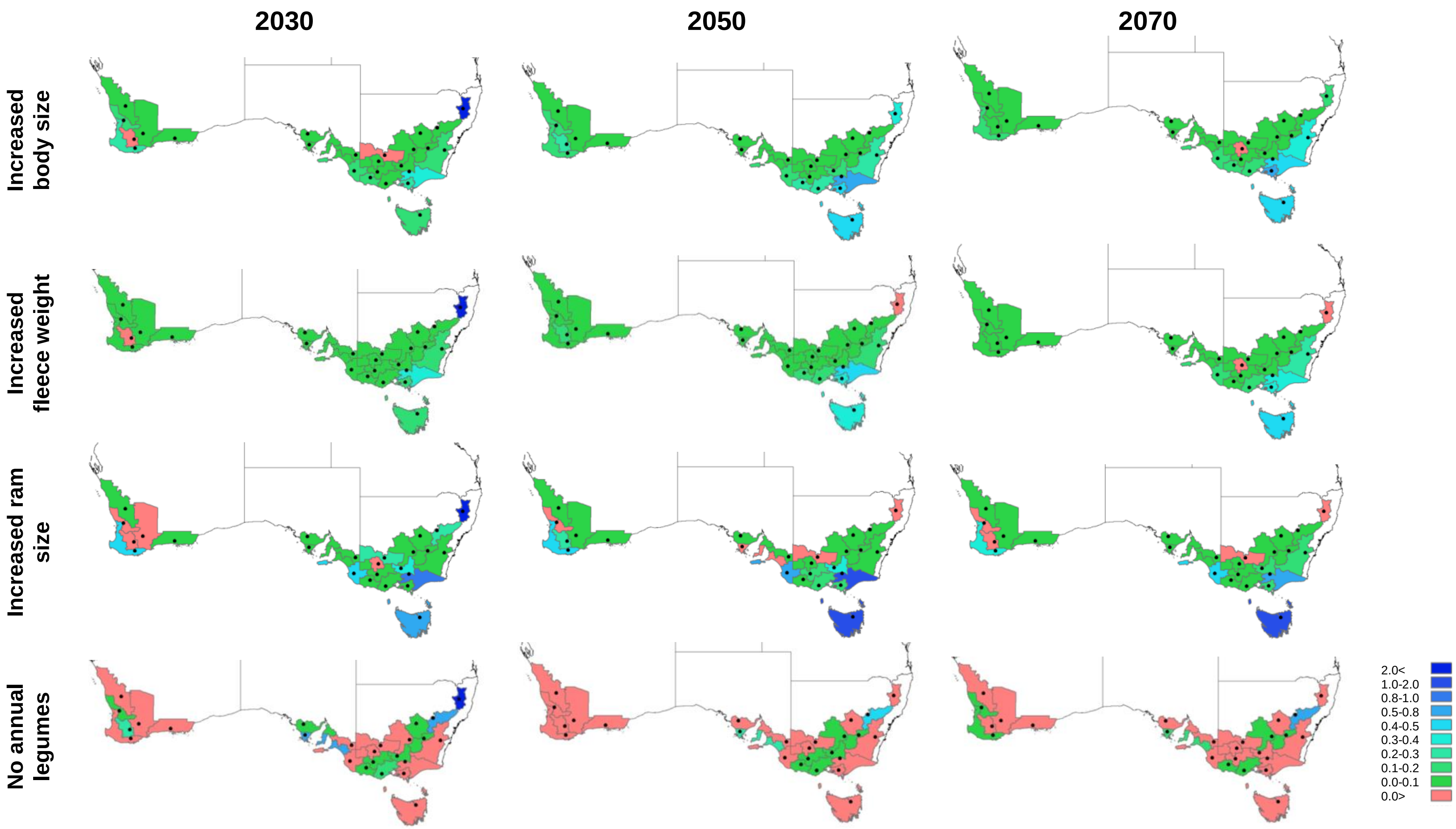
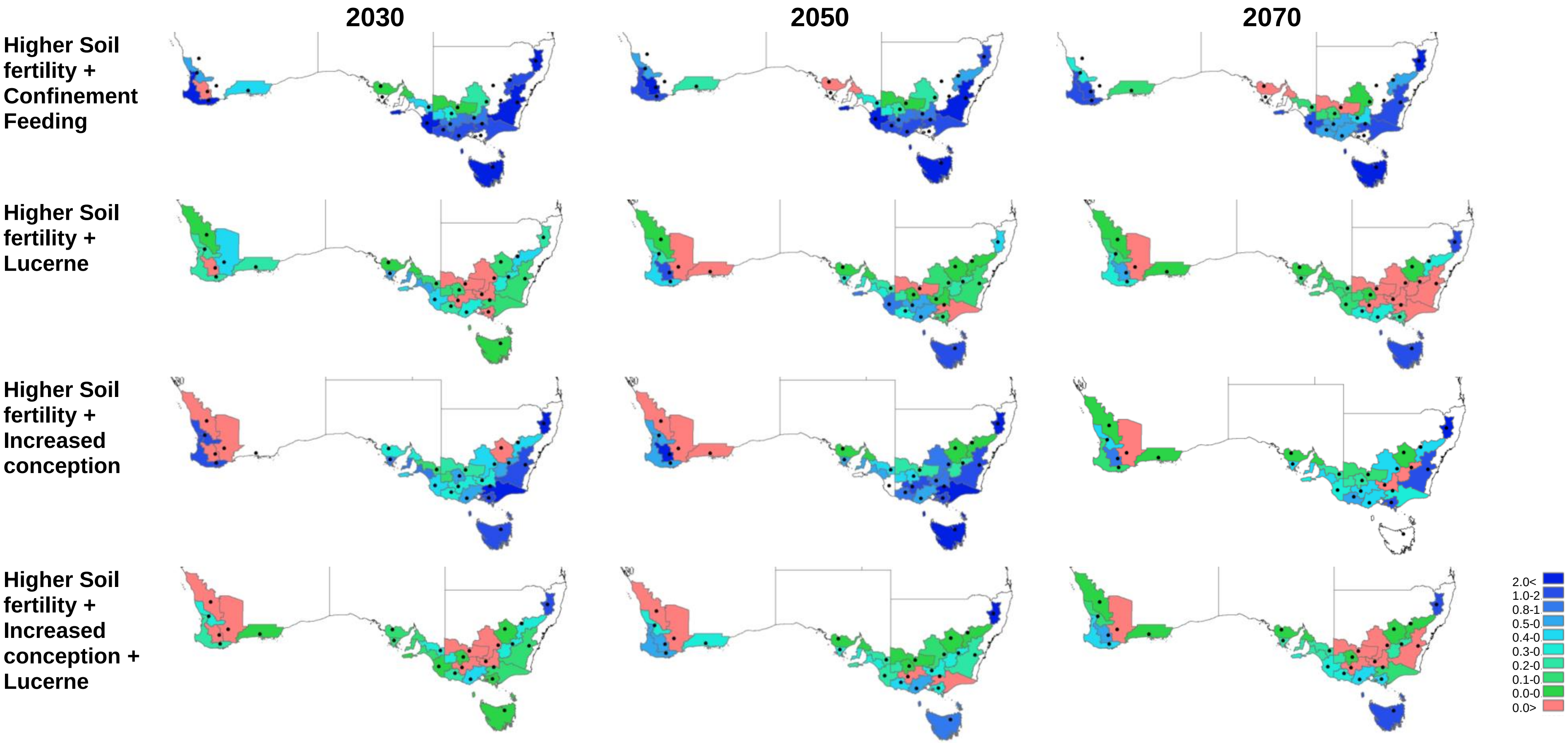


Figure A8.6. Relative effectiveness of four combinations of adaptations in recovering the impact of climate change on the total value of Merino ewe production at 25 locations across southern Australia (0.0 = no benefit; 1.0 = a return to the 1970-99 baseline value of production). Adaptation combinations were applied whether or not they increased profit at the sustainable optimum stocking rate. Values are averages over 4 GCMs. See Table A8.4 for details of the adaptation combinations.



Combination of adaptation strategies

The effect of a combination of adaptation strategies will not be simply the sum of the individual effects, because of complex interactions among biophysical and economical factors. As an example, Table A8.4 and Figure A8.6 show the relative effectiveness of four combinations of adaptations for Merino ewe enterprises. At 2030, at least one of these four combinations is more effective than the best single adaptation at 4 of the 25 locations (Lucindale, Goulburn, Bakers Hill, and Armidale); this expands to 6 and 10 of the 25 locations at 2050 and 2070 respectively. For these four combinations of adaptations, overall relative effectiveness was greater at 2050 than at 2030 or 2070. The combinations of higher soil fertility with confinement

Table A8.4. Relative effectiveness of four combinations of adaptation options for Merino ewe enterprises in recovering the total value of livestock production at 25 locations across southern Australia (0.0 = no benefit; 1.0 = a return to the 1970-99 baseline value of production). For this table, adaptations were applied whether or not they increased profit at the sustainable optimum stocking rate. Values are averages over 4 GCMs. The smallest increase in soil fertility, sowing of lucerne on 20% of land area and confinement feeding with a threshold pasture mass of 2000 kg/ha have been used in the results presented here.

Higher soil fertility		Yes			Yes			Yes			Yes	
Confine't feeding		Yes										
Add 20% lucerne					Yes						Yes	
Conception rate								Yes			Yes	
	2030	2050	2070	2030	2030	2050	2030	2050	2070	2030	2050	2070
Western Australia												
Dalwallinu	0.00	0.00	0.00	0.08	0.06	0.01	-0.61	-0.09	0.02	-0.61	-0.09	0.02
Bakers Hill	0.79	0.65	0.34	0.27	0.26	0.13	1.18	0.73	0.41	0.38	0.35	0.19
Lake Grace	0.00	0.00	0.00	0.48	-0.06	-0.09	-0.48	-0.06	-0.09	-0.48	-0.05	-0.09
Katanning	-3.52	4.91	1.22	-0.26	1.84	0.66	-1.59	2.93	0.85	-0.21	0.67	0.73
Esperance	0.41	0.29	0.17	0.20	-0.01	0.08	0.00	0.00	0.09	0.09	0.30	0.10
Mount Barker	2.32	1.51	1.05	0.24	0.41	0.35	1.42	0.71	0.17	0.28	0.60	0.42
South Australia												
Kyancutta	0.03	0.00	0.00	0.01	0.02	0.01	0.32	0.03	0.02	0.14	0.03	0.03
Cummins	0.00	0.00	0.00	0.55	0.31	0.11	0.87	0.58	0.40	0.12	0.34	0.26
Lucindale	2.47	2.46	1.21	0.47	0.87	0.15	0.45	0.00	0.32	0.06	0.23	0.36
Lameroo	0.41	0.36	0.16	0.11	0.24	0.18	0.13	0.45	0.21	0.30	0.23	0.22
Victoria												
Birchip	0.40	0.29	0.10	0.11	0.03	0.06	0.52	0.44	0.25	0.03	0.04	0.08
Colac	1.38	1.43	0.61	0.39	0.69	0.40	0.58	0.78	0.47	0.42	0.68	0.44
Stawell	0.97	0.95	0.62	-0.30	0.53	-0.15	0.36	1.16	0.47	-0.12	-0.28	-0.15
Swan Hill	0.07	0.03	-0.03	-0.06	-0.10	-0.07	0.25	0.23	0.14	-0.55	0.00	-0.07
Tatura	0.82	0.91	0.49	-0.09	0.03	-0.05	0.40	0.85	-0.10	-0.72	0.32	-0.15
Mansfield	1.54	1.64	1.09	0.16	-0.71	-0.02	2.30	2.32	0.39	0.10	-0.08	0.11
Hamilton	1.28	1.44	0.79	0.23	0.38	0.31	0.32	0.87	0.53	0.30	0.43	0.36
New South Wales												
Armidale	3.95	1.65	2.07	0.27	0.43	1.36	6.38	5.39	3.71	1.40	2.46	1.02
Condobolin	0.00	0.00	0.00	0.11	0.03	0.02	-0.02	0.04	0.04	0.09	0.03	0.03
Cootamundra	0.00	0.00	0.00	0.30	0.26	-0.11	0.76	0.25	-0.02	0.35	0.31	0.30
Goulburn	2.32	2.28	1.76	0.11	0.13	-0.78	1.46	1.25	1.27	0.19	0.26	-0.61
Narrandera	0.22	0.26	0.04	-0.07	0.18	-0.15	0.47	0.92	0.42	-0.41	0.16	-0.17
Wellington	1.15	0.76	0.62	0.42	0.03	0.38	0.40	0.07	0.44	0.31	0.03	0.01
Tasmania												
Launceston	2.26	3.97	3.57	0.04	1.09	1.09	1.20	3.28	0.00	0.04	0.92	1.48

feeding and higher soil fertility with increased conception rate were more effective than the other two combinations; surprisingly, the three-way combination of higher soil fertility, increased conception rate and adding lucerne was more effective than higher soil fertility and increased conception rate alone in only 15 of 75 possible date x location combinations; this three-way combination only out-performed the best single adaptation for Kyancutta at 2070.

Changes in profitability over time after combinations of adaptations

The results of simulations implementing combinations of adaptations for the Merino ewe enterprise are compared with simulations with no adaptations in Figure A8.7.

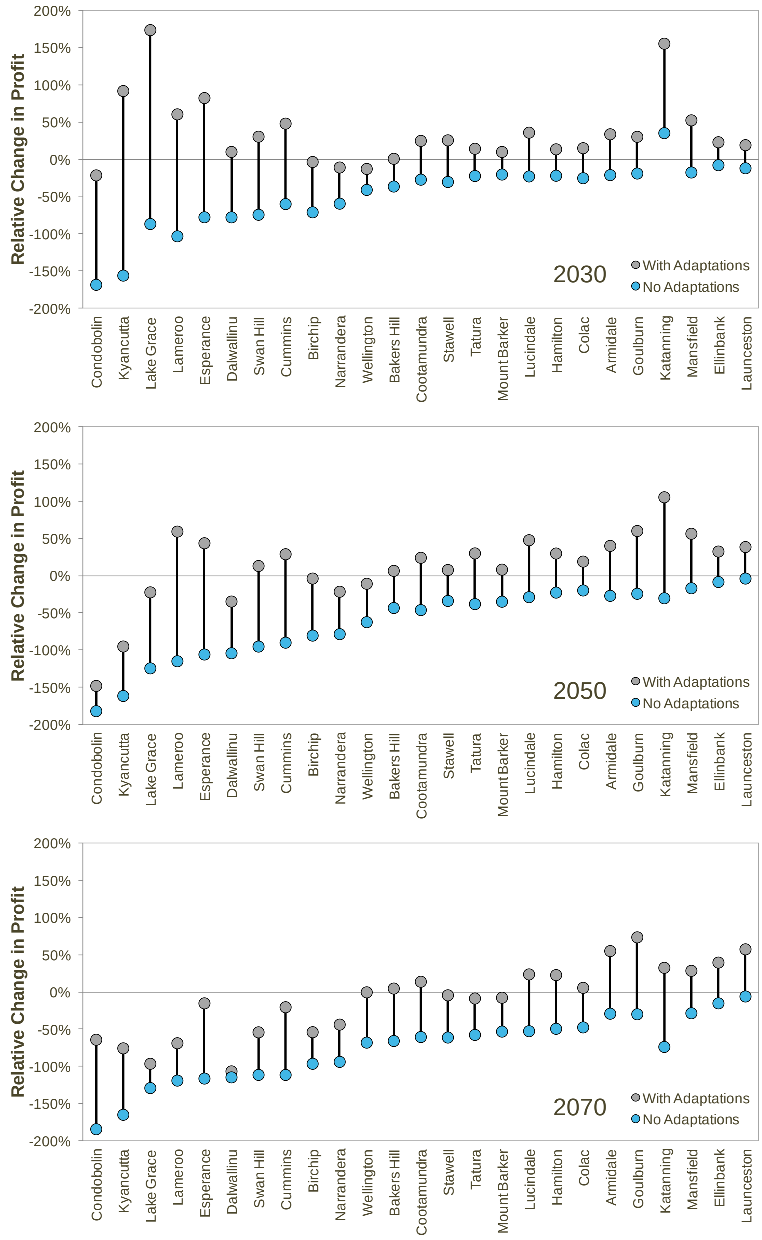


Figure A8.7. Change in profitability of Merino ewe enterprises at 25 locations across southern Australia under projected future climates before (blue circles) and after (grey circles) the introduction of the best-available, locally-specific combination of adaptation options. Profitability values are averages over 4 GCMs and are given as changes relative to profit 1970-99 climate, so that 0% denotes historical levels of profitability and values below -100% denote4 systems that operate at a long-term average loss. Locations have been arranged in decreasing order of climate change impact on profitability (averaged over 203, 2050 and 2070).

The actual combinations of adaptations represented in Figure A8.7 are very different from location to location, being selected from either the systematic combinations of adaptations (e.g. Table A8.5) or the "locally-best" combination of up to 3 adaptation options. At 2030, the best combination of adaptations that we have been able to identify is sufficient in nearly all cases to return these grazing systems to their 1970-99 levels of profitability; there is a tendency for the locations at which climate change impact is greatest to show the greater effectiveness of the adaptations that have been examined.

This picture changes at 2050 and 2070. At these dates the magnitude of climate change impacts on profitability generally becomes greater, and the degree of recovery of profitability from adaptation at the highly-impacted locations (mostly at the dry margin of the cereal-livestock zone) becomes smaller, so that major reductions in profitability remain even after adaptation of the grazing systems.

Conclusions

Modelling different pasture management and livestock genetic adaptation options has demonstrated the effectiveness of such strategies to recover decline in pasture and livestock production. Effectiveness of adaptation strategies varied widely among locations, over time and under the four examined projected future climates. Adaptations would potentially recover decline in income under average effect of examined GCMs.

No single adaptation will be able to return income of enterprises to the historical period (1970-1999), demonstrating a requirement to combine applicable single adaptations. Applying combined adaptations would be especially helpful at later dates, when the increased negative effect of climate change means that single adaptations are likely to be less able to recover declines in production.

There were high uncertainties of applying any given adaptation approach across Southern Australia, because of high variation of rainfall, CO_2 concentration and temperature under different GCMs. This will cause challenges for implementing adaptation strategies, and require the adoption of more complex and combined adaptation strategies, which will differ among locations due to the site characteristics and projected climate.

It is likely that in 2030, combinations of adaptations can be found to return most livestock production systems to profitability. By 2050 and 2070, on the other hand, our findings suggest that the lower-rainfall parts of the cereal-livestock zone will require either new technologies, a complete re-thinking of the feedbase or else sustained price increases in order for livestock production to remain viable.

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Appendix 9. Testing the responses of the GRAZPLAN model to increased atmospheric CO_2

Introduction

As part of the AWI project WP321 on impacts of climate change on pasture and livestock productivity, modifications were made to CSIRO's GRAZPLAN model (Donnelly *et al.* 2002) to simulate the response of pasture species to changes in atmospheric carbon dioxide concentration, [CO_2]. Response functions and parameters were developed based on a review of Australian and international literature on the effects of elevated [CO_2] on the growth and physiology of various pasture species (Project WP321 milestone TMS02 and TMS03 reports). In the reviewed studies elevated [CO_2] was imposed either in controlled environment growth chambers, greenhouses, open- and closed-top chambers in the field or free-air CO_2 enrichment in the field.

For the processes or factors listed below there were relatively consistent responses to elevated [CO_2] in the literature and these were incorporated in the GRAZPLAN model:

- increased assimilation rate;
- reduced transpiration rate;
- decreased specific leaf area (SLA) and
- reduced leaf nitrogen (N) concentration.

When assimilation is radiation limited it is modelled to increase as a function of increased [CO_2] relative to reference [CO_2] of 350 µmol mol^{-1}. The parameters required to model this are related to the CO_2 compensation point (CO_2 concentration at which net CO_2 assimilation is zero) and the variation of the compensation point with temperature; parameters were established for C3 and C4 grasses.

Reduced transpiration at elevated [CO_2] occurs because of the relationship of increasing stomatal resistance with increasing [CO_2]. Parameters for the relative change in stomatal resistance with a doubling of reference [CO_2] were derived for *Lolium* spp, other C3 grasses, C4 grasses and dicotyledons.

Observations in the literature of reduced SLA at increased [CO_2] were used to derive values for a proportional decrease in SLA at doubling of reference [CO_2] for the functional groups C_3 grasses, C_4 grasses, legumes and other dicotyledons.

Several studies showed that leaf N concentration decreased with elevated [CO_2]. Therefore a general function was introduced whereby the maximum and minimum N concentration of leaves decreased linearly to be 10% lower at double reference [CO_2].

Other responses to [CO_2] were observed in the literature, such as changes in assimilate allocation including root:shoot ratios, in nutrient allocation, in phenological development and in competitive interactions in mixed species communities. However, the responses were conflicting or inconsistent and general trends or relationships could not be drawn. Some of these factors may nevertheless have important implications for pasture growth under elevated [CO_2].

In order to test the test how well these modifications predicted pasture response to [CO_2] we used GRAZPLAN to simulate several experiments in which pasture was grown at elevated [CO_2]. Three initial studies were identified, by Lutze and Gifford (1998), Lilley *et al.* (2001) and Volder *et al.* (2004), chosen both because of relevance and potential availability of data. These experiments were included in the literature review from which functions and generalised parameters were established for predicting pasture responses to increased [CO_2]. However, the response functions were of a general nature based on many studies and the details of any one study were not incorporated. We examined the above-mentioned studies in detail and compared GRAZPLAN predictions with observed data.

Elevated [CO_2] experiments chosen for model testing

Lutze and Gifford (1998) measured the effect of [CO_2] and nitrogen supply on the growth of *Danthonia richardsonii* in a glasshouse study at the Australian National University in Canberra, ACT. The plants were grown as “microcosms” in rectangular boxes in glasshouses; the aim was to simulate swards of pasture, considered more representative of field conditions than isolated plants. The microcosms were grown for four years at 360 or 720 µmol mol^{-1} in combination with mineral nitrogen supply of 2.2, 6.7 or 19.8 g N m^{-2} y^{-1}. Biomass was sampled every 6 months; some microcosms were non-destructively harvested with biomass above 8 cm height removed and weighed, while other microcosms were destructively sampled for total above- and below- ground biomass, carbon and nitrogen contents. Lutze and Gifford (1998) found significant growth enhancement under elevated [CO_2], with the highest growth under high N supply but enhanced growth even under restricted N supply. The effect of elevated [CO_2] did not diminish over the four years of the experiment.

The experimental treatments as described by Lutze and Gifford (1998) were complicated, and changed over the duration of the experiment. Some of the environmental conditions are not well described, making the experiment difficult to simulate. To date we have not had access to data from the experiments; if the data becomes available simulation of the experiment may be more feasible.

Lilley *et al.* (2001) conducted an experiment to assess the effect of elevated [CO_2] and temperature on the growth of two pasture species, *Trifolium subterraneum* and *Phalaris aquatica*. The experiments were performed in enclosed controlled temperature gradient tunnels established on the Ginninderra Experiment Station near Canberra, ACT. We have had access to the raw data from this study, which has made simulation of this experiment relatively straightforward. This experiment and comparison of observed data with GRAZPLAN predictions are described in more detail below.

Volder *et al.* (2004) also examined the combined effect of elevated [CO_2] and warming on the growth of *Phalaris aquatica*, but considered both constant day/night warming as well as greater night-time warming (the latter considered more consistent with trends in global climate change). In addition, Volder *et al.* (2004) measured the effect of frequent versus infrequent cutting of above-ground biomass. Like the Lilley *et al.* (2001) study, Volder *et al.* (2004) performed the experiments in controlled temperature gradient tunnels at Ginninderra Experiment Station. In contrast to Lilley *et al.* (2001) who found little effect of [CO_2] on phalaris growth (see below), Volder *et al.* (2004) found higher above-ground growth, but only during spring when growth rates were generally highest. There was no effect of warming treatment and a negative effect of frequent cutting on total above-ground production.

Although we have not had access to the raw data from the Volder *et al.* (2004) experiment, the environmental conditions under the different treatments are relatively clearly presented. We have simulated the experiment in GRAZPLAN, but the predicted pasture growth rates are much lower than the observed data. Volder *et al.* (2004) commented that they observed high growth rates in comparison to other studies, which they attributed to the high rates of nitrogen fertilization and irrigation in their experiments. Despite simulating these conditions we have not predicted similarly high production. Simulations have shown declining production during summer; this was not evident in the data presented by Volder *et al.* (2004) over two years of growth. Therefore there appears to be issues with the way GRAZPLAN predicts phenology of phalaris; this may be related to altered phenological development under frequent defoliation which is currently not represented by simulations, and could also be due to exposure of the plants to higher temperatures than those at which growth has previously been reported. To resolve this issue may require modification of certain parameters in GRAZPLAN.

Due to the issues in simulating the studies by Volder *et al.* (2004) and Lutze and Gifford (1998) we have not compared predicted and observed data in this report, although we are continuing to work on these simulations. Instead the report is focussed on the Lilley *et al.* (2001) study, which are confident in simulating accurately.

Description of Lilley *et al.* (2001) and simulation in GRAZPLAN

Lilley *et al.* (2001) conducted an experiment to assess the effect of elevated [CO_2] and temperature on the growth of two pasture species, *Trifolium subterraneum* and *Phalaris aquatica* in monoculture and as a mixed sward. The experiments were performed in enclosed controlled temperature gradient tunnels established on the Ginninderra Experiment Station near Canberra, ACT (149.10 E, 35.20 S). The tunnels were 1.25 m wide and high and 12 m long, with polycarbonate walls and a clear Teflon roof. Air was drawn into the tunnel from outside by fans and progressively heated as it travelled through the tunnel by radiation or heaters in periods of low radiation. Fan speed was altered to control the rate of air flow and achieve the target temperature. Each tunnel contained a “field” temperature section with temperature close to ambient and a “warmed” temperature experimental section. For elevated [CO_2] treatments CO_2 was injected into the air inlet section of the tunnel; the concentration was continuously monitored and this determined the injection rate as controlled by a solenoid valve.

The experimental conditions imposed by Lilley *et al.* (2001) were a factorial of the treatments in Table A9.1 to give 12 levels. The [CO_2] treatments were imposed on whole tunnels and replicated three times, the tunnels were split into warming treatments and each [CO_2] by temperature subplot contained the three sward types. Lilley *et al.* (2001) included replicate comparison plots with the three sward types growing outside the temperature gradient tunnels (Figure A9.1).

Figure A9.1. Temperature gradient tunnel imposing CO_2 and temperature treatments as described by Lilley *et al.* (2001). Photograph J. Lilley.

Table A9.1. Experimental treatments imposed by Lilley *et al.* (2001).

Sward type	CO_2	Temperature
Trifolium subterraneum monoculture	Ambient 380 µmol mol^{-1}	Field
Phalaris aquatica monoculture	Elevated 690 µmol mol^{-1}	Warmed + 4°C
T. subterraneum / *P. aquatica* 1:1 mix		

Seeds were sown into the tunnels (except for the outside comparison plots) on the 14th December 1995 with a target density of 235 plants m^{-2}. The swards were harvested from 0.34 m^2 plots on 11 occasions between day 29 and day 348 after sowing, removing biomass above 7 cm height (herbage). On the two final harvests biomass from below 7 cm to ground level was also sampled (plant bases), and on the final harvest below ground root biomass was also measured to a soil depth of 20 cm. Julianne Lilley gave access to the raw biomass data and also provided some data on the environmental conditions inside the tunnels. However, not all conditions were monitored during the experiment and some assumptions were made when simulating the tunnel environment.

The soils were described by Lilley *et al.* (2001) as a yellow podzolic. We estimated soil water holding characteristics from descriptions of a yellow podzolic soil core taken from Ginninderra, given in Tables 5 and 6 in Sleeman (1979) and profile 33A in Stace *et al.* (1968). The profile consisted of a loamy sand A horizon to approximately 50 cm depth over a clay B horizon to 100 cm. The parameters in Table 2 were used.

The temperature for each treatment combination was logged hourly by Lilley *et al.* (2001), and we used this to derive daily minimum and maximum temperatures for the input weather files. Over the experimental period (16th December 1995 to 28th November 1996) the warmed treatment had an average daily maximum temperature approximately 3ºC higher and a daily minimum approximately 4ºC higher than in the

Table A9.2. Soil water holding characteristics used in GRAZPLAN simulations of Lilley *et al.* (2001).

Soil depth (mm)	Saturated water content	Drained upper limit water content	15 bar lower limit water content	Air dry water content	SWCON
0-100	0.45	0.30	0.05	0.01	1.0
100-200	0.45	0.30	0.05	0.01	1.0
200-300	0.45	0.30	0.05	0.01	1.0
300-400	0.45	0.30	0.05	0.01	1.0
400-500	0.45	0.30	0.20	0.02	1.0
500-700	0.43	0.30	0.20	0.02	0.5
700-900	0.43	0.30	0.20	0.02	0.5
900-1100	0.43	0.30	0.20	0.02	0.5

Table A9.3: Average daily minimum and maximum temperature (ºC) over the experimental period (16th December 1995 to 28th November 1996) for different tunnel treatments measured by Lilley *et al.* (2001) and outside tunnel comparison plots (data obtained from Ginninderra weather station records).

[CO_2]	**Temperature**	**Max T**	**Min T**
Ambient	Field	21.9	6.8
	Warmed	24.5	11.3
Elevated	Field	21.5	7.0
	Warmed	24.0	10.8
Outside comparison plot		17.5	6.1

field temperature treatment (Table A9.3). Even without the warming treatment the tunnel environment was warmer than outside; the daily maximum was approximately 4ºC higher while the minimum was only approximately 1ºC higher inside than outside.

The differences in temperature inside and outside the tunnel contributed to differences in vapour pressure deficit (D). It is important to correctly simulate D, as in conjunction with stomatal conductance this drives transpiration rates, therefore affecting the soil water balance and plant water status. There is also a parameter in GRAZPLAN that results in reduced stomatal conductance at increasing D, which results in reduced rates of photosynthesis and thus plant growth. Measurements of D were not presented by Lilley *et al.* (2001), but using the same formula as used in GRAZPLAN based on the daily minimum and maximum temperature, we estimated that the average D over the duration of the study was 0.90 kPa outside the tunnels, 1.42 kPa inside the tunnel with field temperature and 1.46 kPa inside the warmed sections of the tunnels. However, in the experiment by Volder *et al.* (2004) at the same location and with similar conditions, D increased inside the temperature gradient tunnels but the increase was not as high as we calculated from the corresponding temperature data. There may have been slightly higher humidity inside the tunnels; as we could not find data on this, we used the Volder *et al.* (2004) data to make adjustments to the D that was calculated from the minimum and maximum daily temperature recorded by Lilley *et al.* (2001).

Radiation is another factor that has a large impact on plant growth and that was different inside and outside the tunnels. Lilley *et al.* (2001) observed that the Teflon film used for the roof of the tunnels transmitted 96% of visible radiation; a small amount of data was provided from the study which indicated less radiation than this was transmitted. In Figure 2 of Volder *et al.* (2004) it was shown that between 20% and 50% of direct solar radiation was reflected or intercepted by the tunnel structure. This varied daily, but there also appeared to be a seasonal effect whereby a smaller proportion of radiation was transmitted during winter than in spring and summer. Based on these seasonal averages we reduced the radiation level recorded at the Ginninderra weather station by between 20% and 40% and used these values in the weather input files.

The swards inside the tunnels were irrigated; the irrigation frequency and amounts were not given by Lilley *et al.* (2001) except to say that swards were well-watered. We removed all soil water limitation to growth in the GRAZPLAN simulations by setting an irrigation event whenever the soil water content fell below the drained upper limit, with the irrigation amount being that required to return the soil water content to the drained upper limit.

The site was fertilized before the experiment was established and a green manure crop incorporated; prior to sowing the surface 30 cm of soil contained 111 kg ha^{-1} of mineral N, and there was 18.3 kg ha^{-1} of available phosphorous in the top 10 cm of soil. The plots were not fertilized during the experiment.

<u>Comparison of predicted and observed data</u>

Lilley *et al.* (2001) measured enhanced herbage production in the clover under elevated [CO_2], and reduced growth at warm temperature, while there were no treatment effects on herbage biomass in phalaris. The results of our simulations with GRAZPLAN were broadly consistent with these results.

Contrasting the observed and predicted data for the comparison plots outside the temperature gradient tunnels allows initial evaluation of model predictions without the added complication of the treatment effects. In the mixture, cumulative herbage cut above 7 cm over the duration of the experiment was over-predicted in phalaris and under-predicted in clover (Figure 2); the observed and predicted combined cumulative herbage production of the mix was similar. Herbage growth of both monocultures was over-predicted (by 25% in clover and 60% in phalaris); however Lilley *et al.* (2001) noted that plants in the outside plots were slow to establish. This may have been due to the plants being established out of season (i.e. in summer as opposed to autumn), but for unknown reasons this effect was more pronounced in the outside plots than in the tunnels. Accurate predictions are therefore difficult to achieve given the stated uncertainty in experimental conditions.

Clover herbage production was enhanced by elevated [CO_2] at field temperature, by 19% in the monoculture and by 31% in the mix (Figure 2). Warming reduced clover growth; when grown under higher temperature there was no significant difference between cumulative herbage biomass under ambient and elevated [CO_2] and warming at ambient [CO_2] resulted in a 28% decrease in production (Figure 2). Lilley *et al.* (2001) attributed the lower growth of clover at warm temperature to increased rates of respiration, especially during winter when photosynthesis was limited by radiation.

The model predictions of clover herbage growth were within the standard error of the observed data for ambient and elevated [CO_2] at field temperature (Figure A9.2), indicating the [CO_2] response functions in GRAZPLAN accurately simulated clover response to elevated [CO_2]. However, the model predictions were higher than observed when warming was simulated. There was a greater discrepancy in observed and predicted herbage biomass with warming at ambient [CO_2] than at elevated [CO_2] (the latter was predicted within two standard errors of the observed data). There was slightly greater over-prediction towards the end of the experiment in

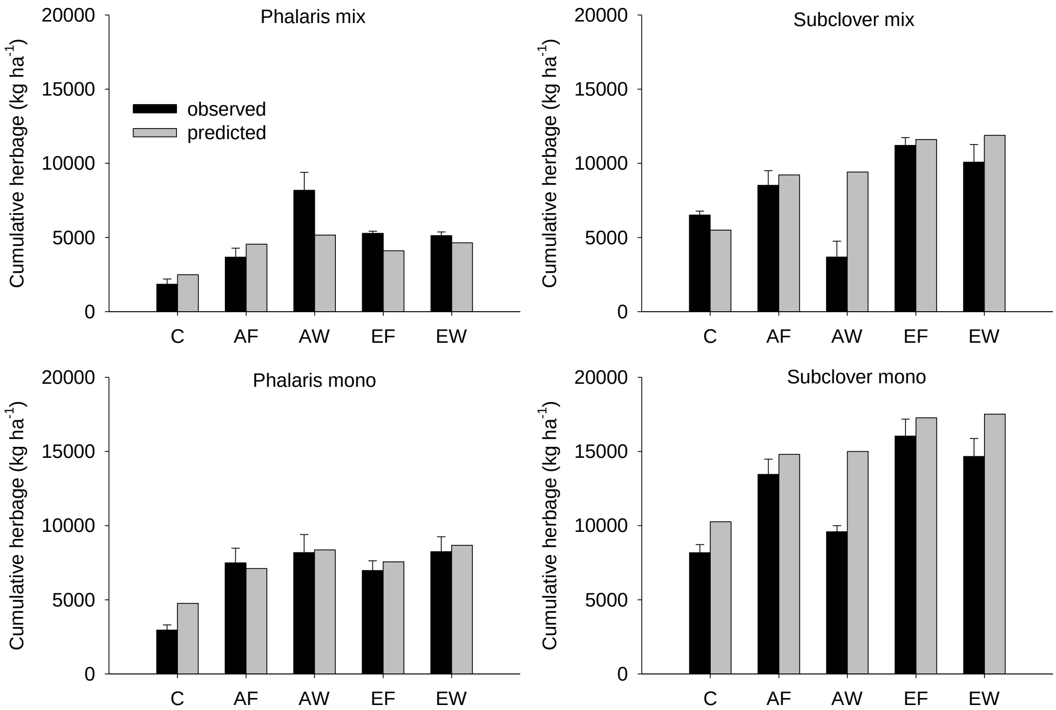

Figure A9.2. Final observed cumulative herbage biomass (greater than 7 cm height) measured by Lilley *et al.* (2001) and predicted with GRAZPLAN on 11 occasions between December 1995 and November 1996. Treatments are C = outside tunnel comparison plots; AF = ambient [CO_2] field temperature; AW = ambient [CO_2] warm temperature; EF = elevated [CO_2] field temperature; EW = elevated [CO_2] warm temperature.

summer (Figures A9.3 and A9.4). Lilley *et al.* (2001) noted that the clover began to senesce in early summer; the model predicted the start of senescence in early December in the field temperature treatment and late October for the warm treatment. It is possible that the timing or rate of senescence was not accurately predicted, but observed data is not available to verify this. It is also possible that temperature effects on respiration or responses to increased vapour pressure deficit at high temperature were not accurately represented by the model. The GRAZPLAN model does include temperature effects on phenology, assimilation, respiration and aging of tissue, and considers plant response to D. However, the increased temperature measured by Lilley *et al.* (2001) in the warmed treatments relative to outside the tunnels (7 ºC higher average maximum temperatures, Table A9.3, and up to 42ºC) are beyond the range considered in GRAZPLAN.

There was no effect of [CO_2] or warming on the cumulative herbage biomass of the phalaris monoculture observed by Lilley *et al.* (2001); the GRAZPLAN simulations produced the same result, with the exception of the outside comparison plots the predicted results were within one standard error of observed data for all treatments (Figure A9.2). Lilley et al. (2001) attributed this lack of [CO2] and warming response to a mild nitrogen limitation. GRAZPLAN results showed a growth limitation by nitrogen during the latter half of the experiment in phalaris monoculture for all treatments.

In contrast to the monoculture, herbage production of phalaris in mixture was enhanced by both elevated [CO_2] and temperature. GRAZPLAN simulations were similar in trend but smaller in magnitude than the observed data (Figure A9.2). In particular, the response to warming at ambient [CO_2] was significantly under-predicted; the observed reduction in clover growth with warming conferred a competitive advantage to phalaris that was not predicted. There was no observed change to the mixture composition with [CO_2] treatment and this was reflected in the model simulations. Treatment effects on the combined phalaris and clover herbage production were accurately simulated.

Although the predicted cumulative herbage production of phalaris was similar to the

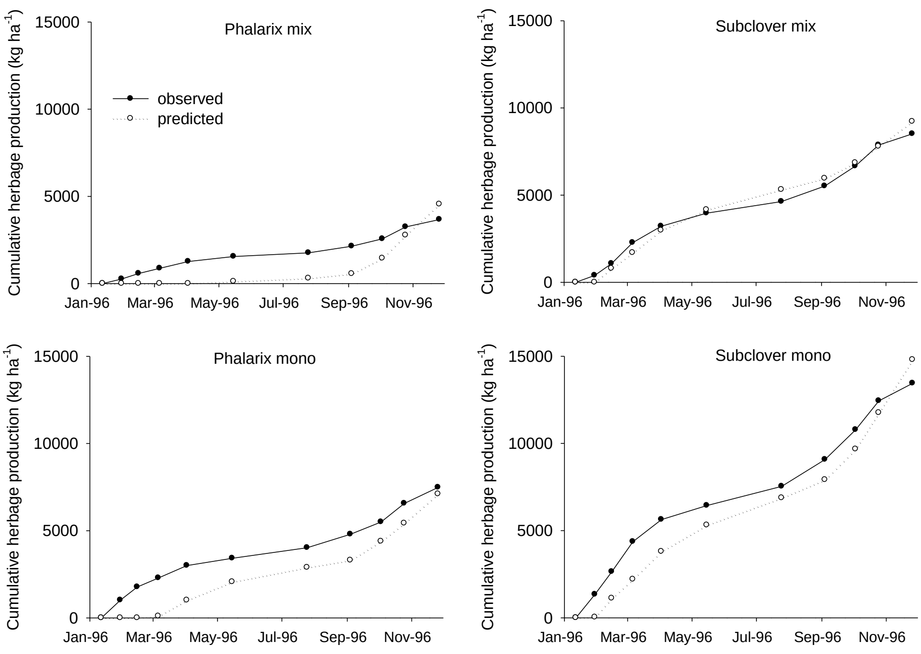

Figure A9.3. Observed cumulative herbage biomass (greater than 7 cm height) over time measured by Lilley *et al.* (2001) and predicted with GRAZPLAN between December 1995 and November 1996, in the ambient [CO_2] field temperature treatment.

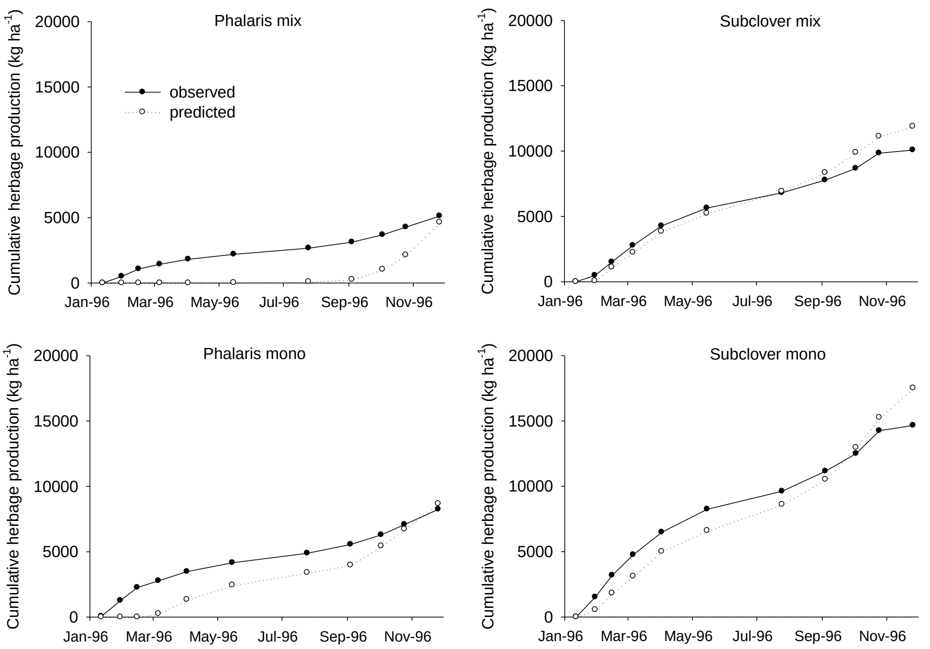

Figure A9.4. Observed cumulative herbage biomass (greater than 7 cm height) over time measured by Lilley *et al.* (2001) and predicted with GRAZPLAN between December 1995 and November 1996 in the elevated [CO_2] warm temperature treatment.

observed data, the timing of growth was different. The predicted early growth was lower than observed, while the later growth was higher. This was observed in all treatments, (for example in the ambient [CO_2] field temperature, Figure A9.3, and elevated [CO_2] warm temperature treatments, Figure A9.4), in both mixture and monoculture. This is unrelated to the CO_2 response functions and may be an issue with simulation of the phenology of phalaris sown out of season (during summer), and with frequent defoliation.

In comparison with herbage biomass, plant base (below 7 cm) and root biomass at the end of the experiment were poorly predicted by GRAZPLAN. The plant base biomass was significantly under-predicted in nearly all cases (Figure A9.5). In addition, while Lilley *et al.* (2001) noted similar treatment effects as occurred for herbage production, there were no or limited treatment effects simulated. After establishment the plant base biomass remained relatively constant over time; this appears to be a general issue with the way allocation was modelled under frequent defoliation and requires further investigation.

Similarly, root biomass was also underestimated by GRAZPLAN and treatment effects were not simulated (Figure A9.6). The discrepancy between predicted and observed data was greatest in the phalaris monoculture. Lilley *et al.* (2001) observed higher root growth under elevated [CO_2] and reduced root growth under warm temperatures. This was attributed partly to phalaris having a greater proportion of total biomass in roots and therefore growth responses being more easily discerned. It was also suggested that the partitioning of biomass to roots increased under elevated [CO_2], which may have explained the lack of response of above-ground biomass. As stated above, changes in allocation and differences in root:shoot ratio have been reported elsewhere in the literature (e.g. Volk *et al.* 2000, Marchi *et al.* 2004). However, the response was variable which made it difficult to extract general relationships; until further data is available this cannot be accurately simulated. The low root biomass predicted by GRAZPLAN was unrelated to treatments. The model predicted sharply declining root biomass at the end of the experiment (summer),

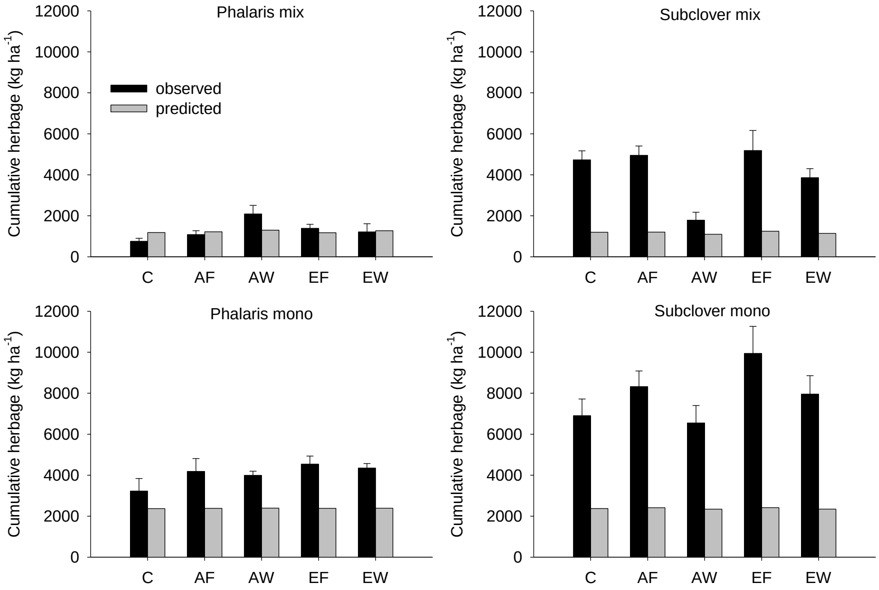

Figure A9.5. Plant base biomass (less than 7 cm height) measured by Lilley *et al.* (2001) and predicted with GRAZPLAN at the end of the experiment in November 1996. Treatments are C = outside tunnel comparison plots; AF = ambient [CO_2] field temperature; AW = ambient [CO_2] warm temperature; EF = elevated [CO_2] field temperature; EW = elevated [CO_2] warm temperature.

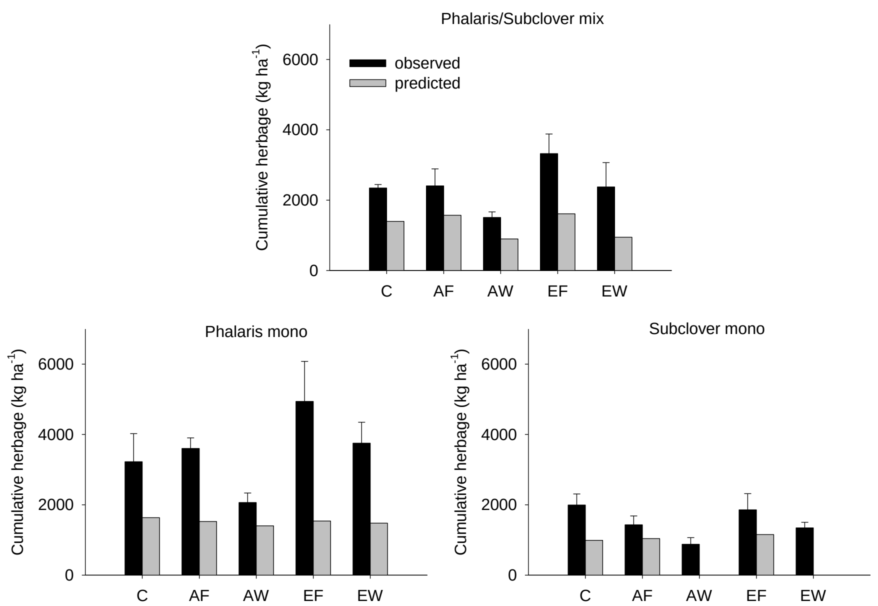

Figure A9.6. Root biomass to 20 cm depth measured by Lilley *et al.* (2001) and predicted with GRAZPLAN at the end of the experiment in November 1996. Treatments are C = outside tunnel comparison plots; AF = ambient [CO_2] field temperature; AW = ambient [CO_2] warm temperature; EF = elevated [CO_2] field temperature; EW = elevated [CO_2] warm temperature.

which may again indicate inconsistencies in the way phenology was modelled for this study.

Conclusions

Application of the [CO_2] response functions incorporated in GRAZPLAN to simulate the study by Lilley *et al.* (2001) resulted in predictions that were relatively consistent with observed data, at least for above-ground biomass. Many of the differences in the predicted and observed data were unrelated to [CO_2] treatment effects and therefore not due to the [CO_2] response functions. Some of the discrepancies occurred due to artefacts of the experimental treatments resulting in different conditions to what would normally be observed in the field. For example, the frequent defoliation may have altered phenological development and simulation of this requires some further modification. In addition, deviation of observed and predicted data was found at high temperatures. Temperature functions are incorporated in GRAZPLAN simulating the responses of phenology, assimilation, respiration and aging of tissue. However, the maximum temperatures in the warmed tunnel treatments were extreme, up to 42ºC in Lilley *et al.* (2001) and 47 ºC in Volder *et al.* (2004). This is beyond the limits of the GRAZPLAN temperature response functions and indeed observations of pasture physiology responses to temperature. This is likely to be important given that elevated [CO_2] is predicted to occur with warmer temperatures in future climate scenarios.

Responses that are poorly or inconsistently represented in the literature, such as allocation of assimilate and particularly root:shoot ratios, may have large effects on growth. Root turnover may also change under elevated [CO_2] which has significant implications for production (Norby and Jackson 2000). These and other uncertainties make predicting production in future climates challenging. Although the applicability of the [CO_2] response functions appears promising, this work represents only an initial testing of these functions and more rigorous testing is desirable.

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Appendix 10. Improving and extending the parameter sets for the GRAZPLAN pasture model

Performance of the GRAZPLAN models in central Victoria

As part of their preparations for producer workshops, Kieran Ransom and Jane Court of DPI Victoria compared GrassGro modelling results with experimental data from two grazing trials in central Victoria. Their initial results suggested that the GRAZPLAN pasture model was under-predicting growth rates in spring; that in phalaris-based pastures, the modelled growing season was continuing too long; and that the timing of the start of the growing season was incorrect in some years. These concerns were strong enough to affect the confidence of DPI staff in being able to use GrassGro for climate change impacts analyses. The spring vs winter growth issue had previously been raised (with less urgency) by program participants working in southern NSW.

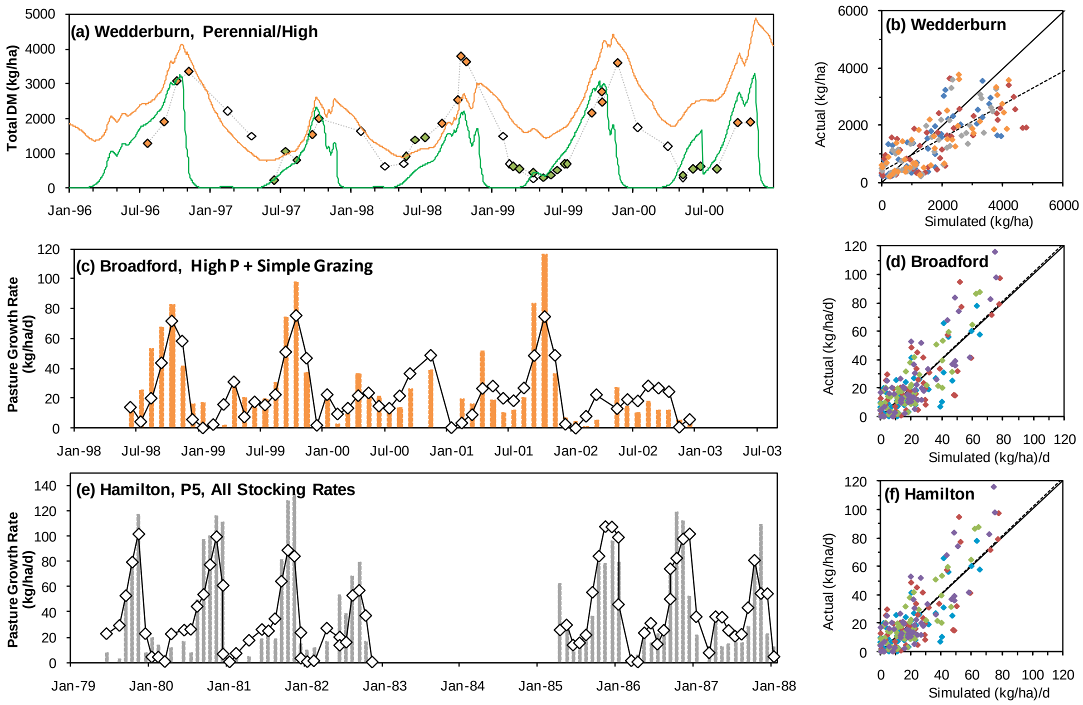
In response, we examined the performance of the GRAZPLAN pasture growth model across a number of locations in Victoria, in order to (i) assess the extent to which these perceived difficulties were borne out by a rigorous comparison with experimental data, and (ii) to correct the pasture growth model to the extent necessary to ensure that it was usable in central Victoria. Three experimental data sets were used for this purpose: the Broadford grazing trial near Seymour (Warn *et al.* 2002), an unpublished grazing trial at Wedderburn near Bendigo (K Ransom, *pers. comm.*), and a long-term phosphorus x stocking rate experiment at Hamilton (Cayley *et al.* 1998).

Weather data were taken from the nearest Patched Point dataset (Jeffrey *et al.* 2001); for Wedderburn, daily rainfall data from a nearby property were superimposed. Soil attributes were taken from measured data at Hamilton and inferred from the available soil descriptions and nearby soil pits at the other two sites. Management of the experimental treatments in each grazing experiment (e.g. fertilizer applications, grazing management, replacement of livestock and application of grass-specific herbicides) was carefully reproduced by implementing the test simulations in the AusFarm modelling software.

Simulations using the default pasture parameter set in version 3.2 of GrassGro confirmed that pasture growth in spring was being significantly under-predicted in this environment, and that for phalaris-based pastures at Broadford the model predicted an end to the growing season that was too late. There were some discrepancies in the germination responses of the model at Broadford but they fell within the expected level of model accuracy for a specific set of conditions. The pasture parameters were therefore modified to resolve the problems with the pattern of pasture growth. Changes were made to alter the description of the phenology of phalaris so that it is predicted to commence reproductive growth much earlier under Victorian conditions, and to flower somewhat earlier as well; to set radiation use efficiency so that it no longer varies with radiation intensity for C_3 species; to shift the temperature responses of phalaris, perennial ryegrass, annual grasses and legumes and capeweed so that growth is more sensitive to low temperatures; and to slow the decay rate of the digestible portion of dead herbage. As part of the parameter modification process, validation simulations of several other grazing experiments in WA, Victoria, SA and NSW were also re-run to confirm that the GRAZPLAN models still gave credible results at those locations with the altered pasture parameter set.

A subset of the results of the validation simulations with the corrected pasture parameter set is shown in Figure A10.1. While there are still specific points where the GRAZPLAN models mis-predict the dynamics of these pastures, the overall level of

Figure A10.1. Selected results of validation simulations at three Victorian locations with the modified pasture parameter sets developed during the project (a, c, e) Time courses of pasture mass (Wedderburn) or pasture growth rate (Broadford and Hamilton) compared against measured data for one of the experimental treatments at each site. (b, d, f) Comparison of actual vs modelled pasture mass or growth rate across all modelled treatments in each experiment. Only the continuously-stocked and simple rotation treatments were modelled at Broadford.



accuracy is comparable to other validation tests, (for example in southern NSW where GrassGro is used with confidence by advisors and consultants). Long-term simulations with GrassGro (not shown here) have confirmed that the month-to-month pattern of pasture growth and composition predicted at Seymour is much more realistic with the modified parameters.

The new parameter set was distributed to Victorian participants in the Southern Livestock 2030 program immediately, and was “rolled out” to participants in other states at opportune times in their work programmes. It will be incorporated into the standard version of GrassGro at the time of the next software release.

Development of a parameter set for redgrass

There is a substantial area of central and northern New South Wales where native pastures containing C_4 perennial grasses are an important part of the feedbase. If the GrassGro decision support tool was to be used for climate change impacts and adaptation studies in these regions then this pasture type needed to be available in its underlying pasture growth model.

We therefore developed a parameter set for the GRAZPLAN pasture growth model that represented the C_4 native perennial grass species, redgrass (*Bothriochloa macra*). In the NPICC temperate pastures database (Pearson *et al.* 1997), redgrass is recorded as the most common C_4 species overall.

Methods

Pasture parameter development proceeded by a combination of literature review together with validation/calibration simulations against datasets from grazing experiments.

Experimental datasets. Relatively few experiments have been conducted on redgrass-dominant pastures. For this study two datasets were acquired: a stocking rate experiment at Armidale, NSW (Roe *et al.* 1959) and a stocking rate x grazing management experiment at Barraba, NSW (Lodge *et al*. 2003).

- *Roe 1948-52 trial* (Roe *et al.* 1959). This experiment was conducted over four years on low-fertility native pastures dominated by redgrass but with a small annual component. There were four treatments: three stocking rates under continuous grazing and a rotational grazing system at the intermediate stocking rate. The experiment also compared livestock performance with and without helminth parasite control, but only the animals with helminth control have been considered here.
- *Lodge 1998-2001 trial* (Lodge *et al.* 2003). This experiment formed part of the Sustainable Grazing Systems Key Program of Meat & Livestock Australia. It was conducted over three years on low-fertility native pastures dominated by redgrass and wallaby grass (*Austrodanthonia* spp.) Five combinations of pasture fertility, stocking rate and grazing management were compared in this experiment, but in this work only two treatments were considered:
  "C6" – continuous grazing at 6 ewes/ha, no fertilizer
  "R4/12" – rotational grazing of four subplots for 4 weeks, 4 ewes/ha, no fertilizer.

Experimental datasets were acquired in electronic form from their custodians or (for the older experiments) by digitization of figures and tables in published papers. The kinds of data that were available and the level of detail varied from experiment to experiment, both for site characteristics and for the dynamics of the soils, pastures and animals. The management of the experimental plots was diverse, including activities such as sowing of pastures, fertilisation at varying rates, irrigation, cutting, herbicide application and rotational grazing.

Weather datasets for the experimental locations and dates were often incomplete (e.g. at some locations only monthly summaries were available). Where necessary therefore, the available weather data were disaggregated and interpolated to produce inferred daily weather time sequences, using a Patched Point dataset from the SILO website (Jeffrey *et al*. 2001; http://www.longpaddock.qld.gov.au/silo) as a reference. Site-specific soil and pasture characteristics (horizon depths, bulk densities, soil moisture characteristics, pasture species included in the models, maximum rooting depths etc.) were set as far as possible to those reported in publications or described in personal communication with the authors. Where necessary, soil characteristics were taken from McKenzie *et al.* (2001) and pasture attributes were drawn from experiments at nearby sites.

Modelling of experiments. In order to accurately reflect management activities, all experiments were modelled using the AusFarm software (Moore 2001). Apart from the management rules, the model configurations that were used were compatible with the GrassGro decision support tool, i.e. the water balance model in GrassGro was used and responses of growth to soil fertility were modelled by using a common "fertility scalar" for all pasture species in each plot.

For each species, a parameter set was developed by working step-by-step through a series of key physiological processes that together make up the dynamics of a pasture:

- the annual cycle of phenology (for example times of flowering and senescence);
- the capture of light and uptake of water by the plant, including consideration of the rooting depth;
- the conversion of these resources to net primary productivity (NPP), including the effect of temperature on growth rate;
- the allocation of NPP to different parts of the plant. In this case allocation to leaf, stem, and root was considered since in these perennial grasses seed and seedling dynamics could be neglected;
- changes in the nutritive value (in particular dry matter digestibility) of green and dry pasture;
- death, litter fall and the disappearance of dry pasture;
- the effect of pasture morphology and tissue structure on the grazing behaviour of livestock.

For each of these processes, the behaviour of each species was described by setting the value of a set of numbers (known as parameters) that govern the equations of the GRAZPLAN pasture model. The importance of these parameters differs – the behaviour of the model is very sensitive to some parameters, and these are the ones that have the most attention devoted to them. Parameterisation was conducted by manually altering coefficients used in the equations of the pasture growth model, running a simulation of each relevant experiment and assessing the goodness of fit between measured and modelled values.

Statistical assessment of model performance. Model performance was assessed using the root mean squared deviation (RMSD) between modelled predictions and measured values. MSD was also partitioned into components (squared bias, non-unity slope and lack-of-correlation; Gauch *et al.* 2003) in order to examine the degree of translation, rotation and scatter, respectively, when measured data were plotted against modelled values. This approach was followed as each component of the MSD is distinct and additive, has a straightforward geometric interpretation and relates transparently to regression parameters (Gauch *et al.* 2003), and so gives a better overall insight into model performance.

Results

In the interests of brevity, only selected results from the simulations of experimental results have been presented.

Roe 1948-52 experiment. This experiment was simulated as a four-species mixture of redgrass, *Austrodanthonia*, subterranean clover and capeweed (as a generic dicotyledonous annual). As shown in Figure A10.2(a), the dynamics of both green and total herbage mass were quite successfully modelled (green: RMSD = 204 kg/ha; total: RMSD = 398 kg/ha). The characteristic high ratio of dead to green mass throughout the year was successfully captured. Bias was small for green mass and the relationship between actual and modelled green mass did not depart significantly from the 1:1 line. For total mass, however, modelled values were higher than actual for high herbage masses and lower than actual at low herbage masses. The simulation of botanical composition (Figure A10.2(b)) was pleasing: the modelled pasture retained all four functional groups and the annuals appeared as only small components of the pasture. The pasture was described by Roe *et al.* (1959) as redgrass-dominant, so the ratio to redgrass to *Austrodanthonia* was probably somewhat too low. In order to both produce the pasture growth rates measured in the experiment and maintain a sensible pasture composition, a very low fertility scalar

Figure A10.2. Simulation of an unfertilized redgrass-dominant pasture at Armidale, NSW stocked at 2.5 dry sheep/ha between October 1948 and October 1952. (a) Actual (symbols) and modelled (lines) green and total herbage mass, (b) actual (LHS) and modelled (RHS) botanical composition by weight at 12 measurement dates Note that the data set does not distinguish between grass species, so that the grey bars the proportion of grass (i.e. redgrass+*Austrodanthonia*).

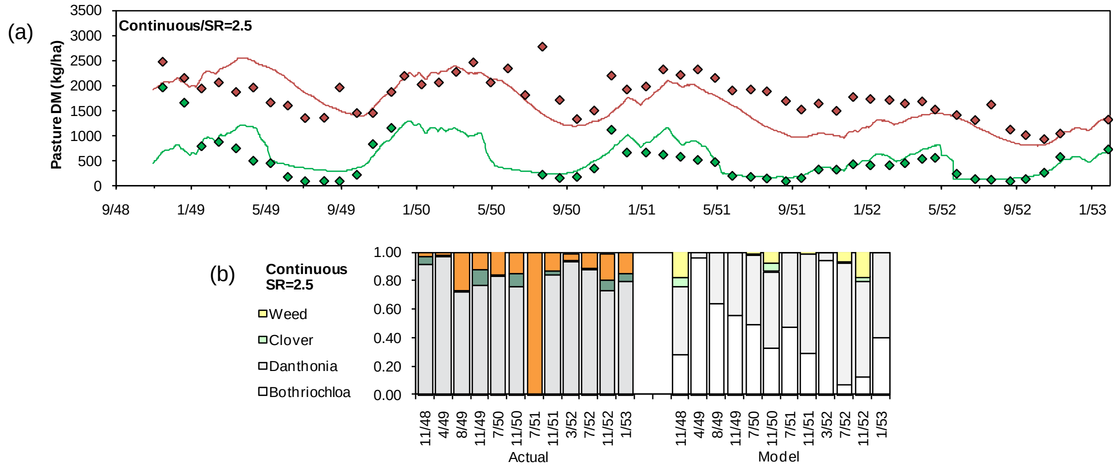
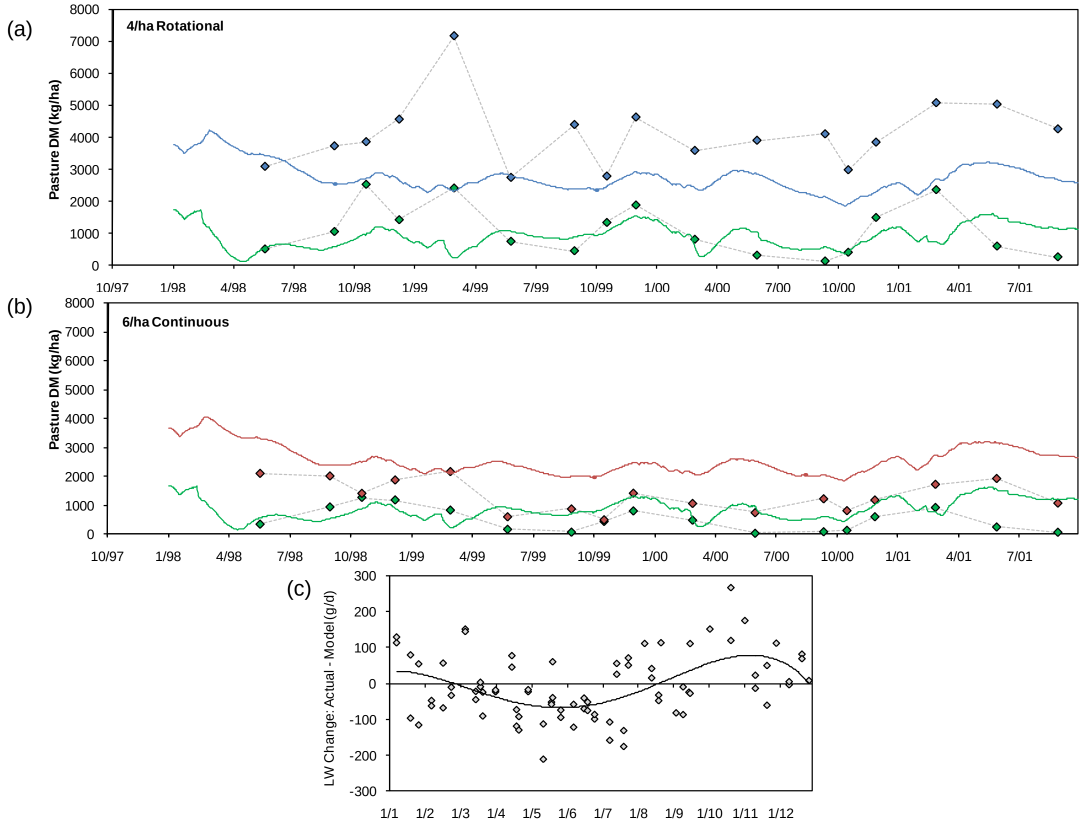


Figure A10.3. Simulation of unfertilized redgrass-dominant pastures at Barraba, NSW. (a, b) Actual (symbols) and modelled (lines) green and total herbage mass for two stocking rate and grazing management treatments; (c) differences between actual and predicted rates of sheep live weight change.



(0.40) had to be set. At higher fertilities, the *Austrodanthonia*, clover and weed components – for which existing parameter sets were used – dominated the pasture.

There was a systematic pattern of under-prediction of sheep weight change in spring each year (Figure A10.2(c)). This mis-prediction was particularly marked in the spring of 1951, when spring growth was correctly predicted as being lower than in other years, but it occurred in all four years of the experiment.

Lodge 1998-2001 experiment. This experiment was modelled as a redgrass monoculture, as redgrass was almost always at least 80% of pasture mass. Results of the validation simulations were not as good as for the Roe 1948-52 experiment (Figure A10.3). While the general patterns of herbage availability were reproduced, the RMSD for pasture mass (green and dead combined) was 1066 kg/ha. There was, however, negligible bias and the relationship between measured and modelled pasture masses did not depart significantly from the 1:1 line. Discrepancies in live weight change predictions showed similar month-to-month variation to the Armidale experiment.

Conclusions

The redgrass parameter sets remains a work-in-progress. However it received a good level of acceptance from NSW Department of Primary Industries staff at a GrassGro training workshop in June 2011, and so a decision was taken to release it for use in *Southern Livestock Adaptation 2030*. It has since been used in NSW regional workshops and in the work presented in Appendices 6 and 7.

Spring is the critical period where further improvement of model predictions is required. This outcome is not especially surprising; the commencement of the pasture growing season is often the most difficult part of describing a new pasture species, mainly because the perennating organs (below-ground reserves in the case of redgrass) are not often measured directly, and because small errors in relative growth rates at the start of growth can result in large changes in predicted pasture mass over 60-90 days.

<u>Development of a parameter set for kikuyu</u>

Kikuyu (*Pennisetum clandestinum*) has long been used as a forage grass in northern and coastal eastern Australia (Mears 1970). Like redgrass, kikuyu uses the C_4 photosynthesis pathway and so can be regarded as "summer-active" species. In the NPICC temperate pastures database (Pearson *et al.* 1997), kikuyu is the second most common.C_4 grass.

Recently, research and producer attention has shifted toward the inclusion of kikuyu in the feedbase in southern Australia (McDowall *et al*. 2003). The primary benefits sought by adding kikuyu to southern Australian pastures include high potential growth rates during late spring, summer and early autumn when growth rates of C_3 species are comparatively low (Neal *et al.* 2010); relatively deep roots that can inhibit rainfall accession to ground water and thus secondary salinisation (Sanford *et al*. 2003, White *et al*. 2003); and the fact that C_4 grasses often display greater water-use efficiency than C_3 species, even in temperate environments (Neal *et al*. 2011). These attributes may also mean that grasses such as kikuyu may be better suited to warmer future climates in southern Australia, especially if rainfall patterns shift toward a greater proportion of summer rainfall.

We therefore sought to develop a kikuyu parameter sets for the GRAZPLAN pasture growth model (Moore *et al.* 1997) that enabled adequate representation of dry matter production, botanical composition and pasture nutritive value.

Methods

As with redgrass, pasture parameter development proceeded by a combination of literature review and validation/calibration simulations against experimental datasets from cutting and grazing experiments.

Experimental data. After considering numerous experiments involving kikuyu, three experiments were chosen for validation work in order to span a range of environments and also on the basis of the completeness of the dataset. The selected experiments were two cutting trials conducted at Taree, NSW (Kemp 1975, 1976) and a grazing experiment at Albany, WA (Sanford *et al.* 2003). Together, these experiments included both a summer-dominant and a Mediterranean rainfall environment and had measurements of dry matter production, botanical composition, soil water content and (where applicable) livestock weights.

- *Kemp 1968-72 experiment* (Kemp 1975). This cutting trial on essentially pure kikuyu swards was conducted as part of a larger forage species evaluation over three seasons. Treatments were irrigation (irrigated vs dryland) x N fertilization (nil, 170 or 680 kg N ha^{-1} yr^{-1}). Shoot dry matter growth rates were measured in six replicates by cutting kikuyu to a height of 7-8 cm with an autoscythe.
- *Kemp 1970-74 experiment* (Kemp 1976). This cutting trial was also conducted over three seasons. Again, pastures were strongly kikuyu-dominant. There were two irrigation treatments (irrigated vs dryland); swards were given a maintenance nitrogen supply.
- *Sanford 1998-2001 experiment* (Sanford *et al.* 2003). The third dataset was from an experiment that formed part of the Sustainable Grazing Systems Key Program of Meat & Livestock Australia.. It was designed to test the impact of tree belts and kikuyu-based pastures on sheep production and groundwater recharge. Pastures included clover and annual grasses as well as kikuyu and were grazed with sheep in an irregular sequence (see Fig. 4a in Sanford *et al*. 2003). Because this experiment provided data on sheep live weight changes it gave an insight into the nutritive value of kikuyu-based pastures as well as competitive interactions with annual C_3-based pastures.

The processes of identifying parameter values, carrying out simulations of the experimental datasets and evaluating simulation results were conducted in a similar way as for redgrass.

Results

Kemp 1968-72 experiment. Shoot dry matter growth rates of the high N, irrigated treatment at Taree are shown in Figure A10.4. Model representation of measured growth rates was reasonable (RMSD = 21 kg/ha/d), though there was some tendency of the model to overestimate lower growth rates (normalised bias = 0.30).

Kemp 1970-74 experiment. Simulation of total dry matter growth of kikuyu for the Kemp 1970-74 data was very good (Figure A10.5). The RMSD was 1044 kg/ha (or about 25 kg/ha/d on a growth rate basis). There were no systematic under- or over-estimation of measured data (normalised squared-bias < 0.01) and the normalised non-unity slope was small (0.02).

Figure A10.4. Shoot dry matter growth rates from July 1969 to December 1972 at Taree, NSW. Open and closed points represent measured and modelled values, respectively.

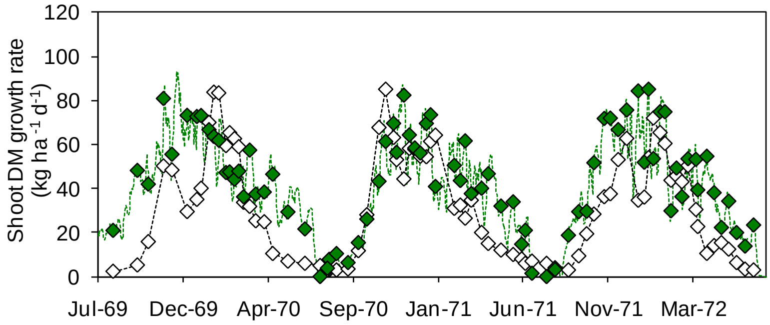


Figure A10.5. Shoot dry matter harvested from July 1971 to August 1974 at Taree, NSW. Open and closed points represent measured and modelled values, respectively.

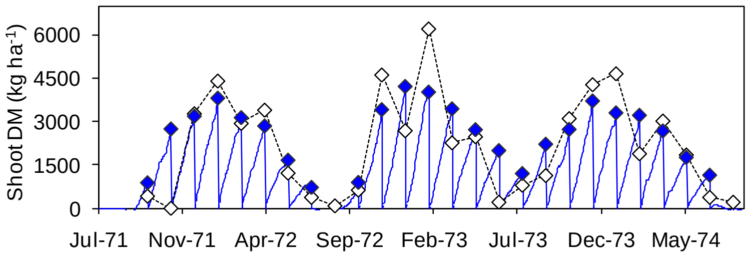
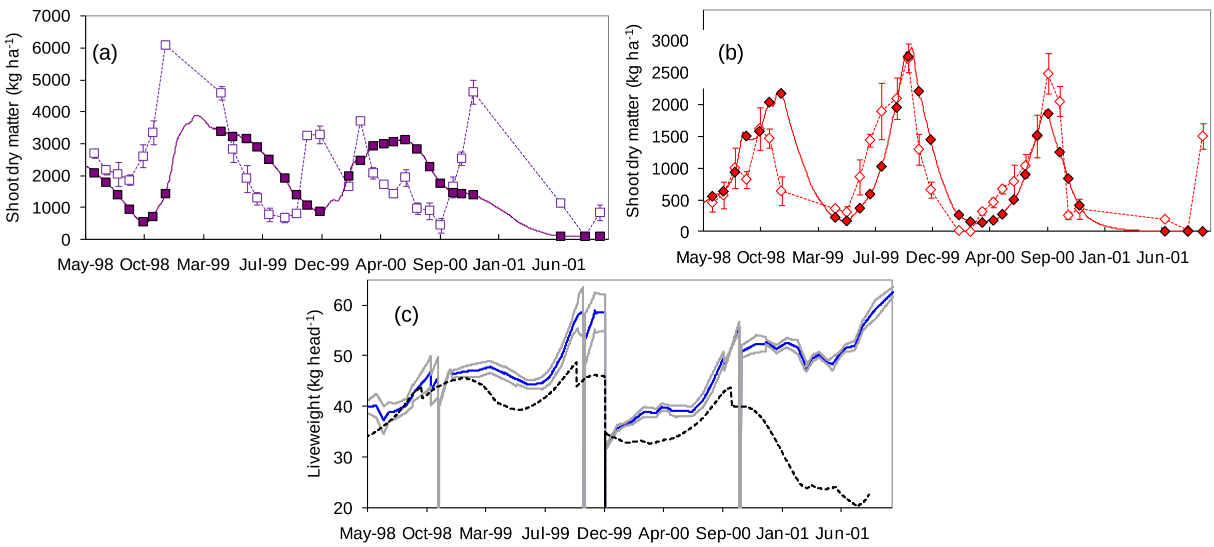


Figure A10.6. Simulation of a kikuyu-subterranean clover pasture grazed by Merino hoggets at Albany, WA from May 1998 to September 2001 . (a) Kikuyu shoot dry matter, (b) subterranean clover shoot dry matter and (c) Merino hogget live weights. Open and closed points in (a) and (b) represent measured and modelled values, respectively, and bars represent standard deviations. Solid blue and grey lines in (c) denote measured sheep live weight means and standard deviations, respectively, and dotted black lines represent simulated live weights. Note that ordinate axes in (a) and (b) differ, and that the ordinate axis in (c) does not begin at the origin.



Sanford 1998-2001 experiment. Simulated shoot dry matter of kikuyu for the Sanford dataset was less accurate than for the Taree trials (Figure A10.6(a), RMSD = 1238 kg ha^{-1}). The current parameter set under-predicts kikuyu growth during the spring of 1998, resulting in peak shoot dry matter values of around 4 t ha^{-1} (vs the 6 t ha^{-1} measured). Subsequent simulated decomposition rates of above-ground litter during winter of 1999 were lower than observed, and regrowth in autumn of 2000 also later than expected. Regrowth during the summer periods of 2001 was not reproduced by the model. The representation of the subterranean clover growing with the kikuyu is very good, on the other hand (Figure A10.6(b)), so that the GRAZPLAN model is simulating the co-existence of the different species reasonably well.

Simulated sheep live weight changes were often below measured values (Fig. A10.6(c)), consistent with the under-prediction of green herbage mass in late spring.

Discussion and conclusions

The kikuyu parameter set is not ready for release, either to GrassGro users in general or to participants in the *Southern Livestock Adaptation 2030* program in particular.

As for redgrass, spring is the critical period where further improvement of model predictions is required. Lack of data on pasture phenology at the experimental sites has also hampered parameter development. The onset of reproductive growth typically produces a shift in allocation of assimilate toward the shoots. Because kikuyu flowers are minute, sub-sessile and enclosed within leaf sheaths (Mears 1970) it is not surprising that the phenology of this species is rarely documented (e.g. see Hacker and Evans 1992). Consequently, assessment of simulated phenology can only be performed in qualitative terms (e.g. by comparison with Carr and Ng Kok 1956 and Mears 1970).

Further work on the kikuyu parameter set is required. An additional data set that may be employed for this purpose is from a cutting experiment at Camden, NSW (Neal *et al.* 2010, 2011), a site that has summer-dominant rainfall but cooler winters than Taree.

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Appendix 11. Characteristics of the locations, land resources and livestock production systems used in the GrassGro modelling of climate change impacts and adaptations

The tables in this Appendix detail the inputs used in the modelling analyses presented in Appendices 5, 7 and 8.

Table A11.1. Clean fleece price as a function of average fibre diameter. The same values are used for all sheep enterprises.

Fibre Diameter (micron)	Clean Fleece Price ($/kg)
17	14.56
18	13.29
20	9.81
21	9.36
22	9.07
26	6.14

Table A11.2. Monthly livestock sale prices in each enterprise. *V*alues are in $/kg carcass weight; sale prices for male and female young stock in the two ewe enterprises are the same. P_{main} is the sale price for cast-for-age stock; P_{male} and P_{female} are the sale prices for male and female young stock, respectively.

Month	Merino Ewe		Crossbred Ewe		Wether	—— Beef Cow ——			Steer
	P_{main}	P_{male}, P_{female}	P_{main}	P_{male}, P_{female}	P_{main}	P_{main}	P_{male}	P_{female}	P_{main}
Jan	2.39	3.60	2.39	4.15	2.39	2.70	3.50	3.31	3.50
Feb	2.44	3.74	2.44	4.32	2.44	2.77	3.58	3.39	3.58
Mar	2.61	3.78	2.61	4.36	2.61	2.81	3.63	3.44	3.63
Apr	2.68	3.78	2.68	4.36	2.68	2.76	3.57	3.39	3.57
May	2.85	3.89	2.85	4.48	2.85	2.78	3.60	3.41	3.60
Jun	3.03	4.07	3.03	4.69	3.03	2.80	3.61	3.42	3.61
Jul	2.61	3.78	2.61	4.36	2.61	3.01	3.89	3.69	3.89
Aug	2.48	3.56	2.48	4.11	2.48	3.06	3.96	3.75	3.96
Sep	2.24	3.42	2.24	3.94	2.24	2.98	3.85	3.65	3.85
Oct	1.99	3.10	1.99	3.57	1.99	2.80	3.62	3.43	3.62
Nov	2.09	3.13	2.09	3.61	2.09	2.77	3.58	3.39	3.58
Dec	2.14	3.31	2.14	3.82	2.14	2.67	3.45	3.27	3.45

Table A11.3. Enterprise-specific costs, prices and multipliers used in the financial calculations

	Unit	Merino Ewe	Crossbred Ewe	Beef cow	Wether	Steer
Ratio of average wool price to fleece price	$/$	0.92	0.92		0.92	
Carcass:live weight ratio – main flock or herd	–	0.42	0.42	0.46	0.43	0.52
Carcass:live weight ratio – male young sale stock	–	0.43	0.47	0.52		
Carcass:live weight ratio – female young sale stock	–	0.42	0.46	0.52		
Skin price – main flock or herd	$/head	5.00	5.00	0.00	5.00	0.00
Skin price – young sale stock	$/head	5.00	2.00	0.00		
Husbandry cost - main flock or herd (annual)	$/head	3.75		9.20	2.00	9.20
Husbandry cost – young stock (birth to sale)	$/head	4.50		5.73		
Cost of shearing sheep in the main flock	$/head	6.00	6.00		6.00	
Cost of shearing young stock	$/head	6.00	6.00			
Variable costs of wool sales (commissions etc)	$/$	0.04	0.04		0.04	
Fixed costs of selling stock	$/head	2.00		37.00	2.00	37.00
Variable costs of livestock sales	$/$	0.05	0.05	0.05	0.05	0.05
Capital value of livestock	$/head	125	125	670	90	500

Table A11.3. Costs of supplementary feeds.

Supplement	Cost ($/kg fresh weight)
Wheat	0.280
Barley	0.255
Oats	0.275
Sorghum	0.240
Lupins	0.320
Hay	0.095
Pea straw	0.095

Table A11.5. Locations and their land resources. Climate statistics are for the period 1970-1999. The "Stubbles?" column gives times of year when stubbles were deemed to be available for grazing.

Location	State	Latitude/Longitude	Annual Rainfall (mm)	Proportion of Rainfall Nov-Mar	Annual Mean Temperature (°C)	Proportion of Area	Soil Description	
Armidale	NSW	30°31'S 151°40'E	778	0.56	13.9	0.5	Prairie soil	Phalar
						0.5	Lateritic podzol	Native
Bakers Hill	WA	31°46'S 116°29'E	594	0.14	17.3	0.8	Deep sand	Annua
						0.2	Deep sand	Lucern
Birchip	Vic	35°59'S 142°55'E	403	0.32	15.6	1.0	Clay loam	Barley
Colac	Vic	38°17'S 143°40'E	699	0.30	13.8	1.0	Gradational clay	Perenn
Condobolin	NSW	33°04'S 147°14'E	470	0.44	17.2	0.8	Red brown earth	Barley
						0.2	Red brown earth	Lucern
Cootamundra	NSW	34°38'S 148°01'E	671	0.38	15.4	1.0	Duplex soil	Phalar
Cummins	SA	34°16'S 135°44'E	408	0.18	16.3	1.0	Clayey red brown earth	Barley
Dalwallinu	WA	30°17'S 116°40'E	366	0.24	19.1	1.0	Red clay	Annua
Ellinbank	Vic	38°15'S 145°56'E	1091	0.34	13.6	1.0	Red Ferrosol	Perenn
Esperance	WA	33°36'S 121°47'E	507	0.25	16.4	1.0	Deep sandy duplex	Annua
Goulburn	NSW	34°49'S 149°44'E	668	0.45	13.1	1.0	Shallow yellow-grey duplex	Phalar
Hamilton	Vic	37°39'S 142°04'E	663	0.29	13.2	1.0	Silty clay loam over clay (white)	Perenn
Katanning	WA	33°41'S 117°33'E	471	0.21	15.9	1.0	Sandy duplex	Annua
Kyancutta	SA	33°08'S 135°33'E	299	0.27	17.2	1.0	Grey calcareous sandy loam	Barley
Lake Grace	WA	33°06'S 118°28'E	352	0.27	16.8	1.0	Yellow shallow sandy duplex	Annua
Lameroo	SA	35°20'S 140°31'E	386	0.29	16.0	0.5	Sandy loam over poorly structured brown clay	Barley
						0.5	Sandy loam over brown clay	Barley
Launceston	Tas	41°32'S 147°12'E	641	0.33	11.6	1.0	Shallow duplex	Perenn
Lucindale	SA	36°58'S 140°22'E	588	0.22	14.8	1.0	Sandy loam on clay loam	Phalar
Mansfield	Vic	37°03'S 146°05'E	735	0.34	13.7	0.6	Deep yellow-grey duplex	Phalar
						0.4	Deep yellow-grey duplex	Native
Mt Barker	WA	34°38'S 117°38'E	693	0.22	15.0	1.0	Loamy sand over medium clay	Annua
Narrandera	NSW	34°45'S 146°33'E	485	0.36	16.5	1.0	Red duplex	Annua
Stawell	Vic	37°04'S 142°47'E	574	0.29	14.1	0.6	Fine sandy clay loam over heavy clay	Annua
						0.4	Fine sandy clay loam over heavy clay	Phalar
Swan Hill	Vic	35°20'S 143°33'E	379	0.36	16.5	1.0	Sandy clay loam	Barley
Tatura	Vic	36°26'S 145°16'E	488	0.35	14.8	1.0	Sandy loam over clay loam	Barley
Wellington	NSW	32°30'S 148°58'E	610	0.45	16.7	0.2	Sandy clay loam over clay	Lucern
						0.5	Sandy clay loam over clay	Phalar
						0.3	Red duplex	Native

Table A11.6. Management of the Merino ewe enterprises at each of the 25 locations. S.R. = stocking rate in ewes per hectare immediately after replacement. Except as noted, a "flexible" grazing management scheme was used in which animals were moved weekly to the paddock that would provide the highest rate of weight gain.

Location	Optimal Sustainable S.R.	Ewe Shearing Date	Average Lambing Date	Earliest Lamb Sale Date	Final Lamb Sale Date	Maintenance Supplement	Grazing Ma
Armidale	4.0	15 Feb	1 Oct	28 Feb		Wheat, whole	Ewes graze native pasture 15 Jan-31 Mar
Bakers Hill	13.1	30 Sep	1 May	1 Oct	30 Nov	Lupins/oats	Lucerne paddock closed 15 Aug-14 Oct
Birchip	4.6	1 Nov	9 Apr	1 Nov		Barley, whole	
Colac	16.3	25 Nov	28 Aug	1 Feb		Barley, whole	
Condobolin	1.4	1 Oct	11 Jun	1 Nov		Wheat, whole	
Cootamundra	7.9	15 Mar	20 Jul	30 Dec		Barley, whole	
Cummins	2.4	1 Nov	15 May	1 Nov	30 Apr	Barley, whole	
Dalwallinu	1.9	30 Sep	1 Jul	15 Dec		Lupins/Barley	
Ellinbank	20.6	25 Nov	13 Sep	1 Feb		Barley, whole	
Esperance	2.0	1 Nov	29 May	1 Nov	15 Mar	Lupins/Barley	
Goulburn	5.9	15 Nov	31 Aug	20 Nov		Wheat, whole	
Hamilton	12.0	25 Nov	13 Sep	1 Feb		Barley, whole	
Katanning	2.1	15 Jan	12 Jul	1 0 Feb	1 Nov	Lupins/Oats	
Kyancutta	1.0	1 Nov	15 May	1 Nov	30 Apr	Barley, whole	
Lake Grace	0.8	1 Nov	29 May	1 Nov	15 mar	Lupins/Barley	
Lameroo	2.2	1 Nov	9 Apr	1 Nov		Barley, whole	Weekly Rotation
Launceston	8.3	1 May	6 Sep	31 Dec		Wheat, whole	
Lucindale	6.6	15 Nov	12 Jun	1 Oct	1 Jan	Barley, whole	
Mansfield	8.1	15 Nov	29 Jun	15 Nov	1 Jan	Barley, whole	Ewes graze native pasture 1 Oct-30 Nov
Mt Barker	10.5	1 Feb	8 Jul	30 Nov		Barley, whole	
Narrandera	5.9	15 Apr	28 Apr	10 Nov	31 Dec	Wheat, whole	
Stawell	7.6	15 Jun	18 Jul	20 Feb		Wheat, whole	1 Sep-14 Nov Ewes graze perennial pasture
Swan Hill	3.6	1 Nov	9 Apr	1 Nov		Barley, whole	
Tatura	6.3	15 Jun	15 Jul	20 Feb		Wheat, whole	
Wellington	4.0	15 Nov	1 Aug	1 Dec	30 Apr	Wheat, whole	Lucerne paddock ewes >1yr excluded 1 Oct

Table A11.7. Management of the crossbred ewe enterprises at each of the 25 locations. S.R. = stocking rate in ewes per hectare immediately after replacement. Except as noted, a "flexible" grazing management scheme was used in which animals were moved weekly to the paddock that would provide the highest rate of weight gain.

Location	Optimal Sustainable S.R.	Ewe Shearing Date	Average Lambing Date	Earliest Lamb Sale Date	Final Lamb Sale Date	Maintenance Supplement	Grazing Ma
Armidale	3.8	15 Feb	15 Jun	1 Jan	31 Jan	Wheat, whole	Perennial pasture grazed 16 Jan – 31 Mar
Bakers Hill	8.5	15 Feb	1 Jun	16 Sep	31 Jan	Lupins/Oats	Lucerne pasture closed 15 Aug – 14 Oct
Birchip	3.3	1 Nov	1 Jun	16 Sep	28 Feb	Barley, whole	
Colac	11.1	25 Nov	1 Jul	16 Oct	28 Feb	Barley, whole	
Condobolin	1.1	1 Oct	1 Jun	1 Oct	28 Feb	Wheat, whole	Weaners to lucerne 1 Mar-31 Oct; lucerne cl
Cootamundra	5.5	15 Mar	1 Jun	1 Dec	28 Feb	Barley, whole	
Cummins	2.0	1 Nov	1 Jun	1 Nov	31 Jan	Barley, whole	
Dalwallinu	1.5	30 Sep	1 Jun	1 Nov	28 Feb	Lupins/Barley	
Ellinbank	13.0	25 Nov	1 Jul	1 Dec	31 Mar	Barley, whole	
Esperance	2.4	1 Nov	29 May	1 Oct	31 Jan	Lupins/Barley	
Goulburn	5.4	15 Nov	15 Jun	1 Dec	15 Feb	Wheat, whole	
Hamilton	7.6	25 Nov	15 Jun	1 Dec	15 Feb	Barley, whole	
Katanning	1.2	15 Jan	12 Jul	1 Oct	31 Jan	Lupins/Oats	
Kyancutta	1.0	1 Nov	29 May	1 Oct	31 Jan	Barley, whole	
Lake Grace	0.4	1 Nov	12 Jul	1 Oct	31 Dec	Lupins/Barley	
Lameroo	1.4	1 Nov	1 Jun	1 Oct	28 Feb	Barley, whole	Weekly rotation
Launceston	5.7	1 May	6 Sep	1 Dec	31 Mar	Wheat, whole	
Lucindale	4.9	15 Nov	1 Aug	15 Nov	28 Feb	Barley, whole	
Mansfield	5.2	15 Nov	15 Jul	15 Nov	31 Mar	Barley, whole	Ewes to native pasture 1 Oct-30 Nov, weane
Mt Barker	8.2	1 Feb	15 Jun	30 Nov	28 Feb	Lupins/Oats	
Narrandera	4.2	15 Nov	1 Jun	1 Nov	28 Feb	Wheat, whole	
Stawell	6.1	15 Jun	15 Jun	1 Nov	28 Feb	Wheat, whole	1 Sep–14 Nov perennial pasture grazed 2 da
Swan Hill	1.1	1 Nov	15 Jun	1 Oct	28 Feb	Barley, whole	
Tatura	5.0	15 Jun	1 Jul	1 Nov	28 Feb	Wheat, whole	
Wellington	3.9	15 Nov	1 Jun	1 Nov	28 Feb	Wheat, whole	1 Oct-31 Dec ewes and 1 Aug-7 Nov weane

Table A11.8. Management of the beef cow enterprises at each of the 25 locations. S.R. = stocking rate in cows per hectare immediately after replacement. Except as noted, a “flexible” grazing management scheme was used in which animals were moved weekly to the paddock that would provide the highest rate of weight gain.

Location	Optimal Sustainable S.R.	Average Calving Date	Earliest Steer Sale Date	Final Steer Sale Date	Target Steer Sale Weight (kg)	Earliest Heifer Sale Date	Final Heifer Sale Date	Target Heifer Sale Weight (kg)	Maintenance Supplement
Armidale	0.60	25 Aug	30 Jun			30 Jun			Wheat, whole
Bakers Hill	1.08	1 Apr	30 Nov			30 Nov			Lupins/Oats
Birchip	0.30	15 Aug	30 Sep (+1)			30 Sep (+1)			Barley, whole
Colac	1.94	23 Feb	15 Dec			15 Dec			Barley, whole
Condobolin	0.15	15 Jun	1 Jun	30 Nov	400	1 Jun	30 Nov	340	Wheat, whole
Cootamundra	0.79	12 Jul	10 Nov (+1)			10 Nov (+1)			Barley, whole
Cummins	0.33	15 Jul	30 Nov (+1)			30 Nov (+1)			Barley, whole
Dalwallinu	0.26	1 Apr	15 Jan			15 Jan			Lupins/Barley
Ellinbank	2.08	15 Aug	15 Jan (+1)			15 Jan (+1)			Barley, whole
Esperance	0.47	18 Apr	15 Jan			15 Jan			Lupins/Barley
Goulburn	0.55	11 Aug	30 Jun			30 Jun			Wheat, whole
Hamilton	1.18	1 Sep	15 Jan (+1)			15 Jan (+1)			Barley, whole
Katanning	0.30	15 Mar	15 Feb			15 Feb			Lupins/Oats
Kyancutta	0.10	15 Jul	30 Nov (+1)			30 Nov (+1)			Barley, whole
Lake Grace	0.04	1 Apr	15 Jan			15 Jan			Lupins/Barley
Lameroo	0.17	15 Jul	15 Jan (+1)	15 Jul	400	15 Jan (+1)	15 Jul	350	Barley, whole
Launceston	1.19	1 Sep	15 Jan (+1)			15 Jan (+1)			Wheat, whole
Lucindale	0.73	15 Jul	15 Jan (+1)			15 Jan (+1)			Barley, whole
Mansfield	0.85	25 Jul	10 Nov	10 Dec	420	10 Nov	10 Dec	400	Barley, whole
Mt Barker	1.18	1 Apr	30 Sep (+1)			15 Dec			Lupins/Oats
Narrandera	0.62	15 Jun	1 Sep (+1)	30 Nov	450	1 Sep (+1)	30 Nov	380	Wheat, whole
Stawell	0.89	15 Jul	30 Nov (+1)			30 Nov (+1)			Wheat, whole
Swan Hill	0.21	15 Aug	30 Nov (+1)			30 Nov (+1)			Barley, whole
Tatura	0.62	15 Aug	30 Nov (+1)			30 Nov (+1)			Wheat, whole
Wellington	0.50	15 Aug	1 Sep (+1)	31 Jan	450	1 Sep (+1)	31 Jan	380	Wheat, whole

Table A11.9. Management of the wether enterprises at each of the 25 locations. S.R. = stocking rate in wethers per hectare immediately after replacement. A “flexible” grazing management scheme was used in which animals were moved weekly to the paddock that would provide the highest rate of weight gain.

Location	Optimal Sustainable S.R.	Purchase Date	Purchase Age (months)	Sale Date	Sale Age (years)	Maintenance Supplement
Armidale	8.4	1 Mar	5	1 Mar	5	Wheat, whole
Bakers Hill	13.8	1 Oct	5	1 Oct	5	Lupins/Oats
Birchip	3.1	1 Nov	7	2 Nov	5	Barley, whole
Colac	18.0	1 Feb	5	26 Nov	5	Barley, whole
Condobolin	3.4	30 Nov	5	2 Oct	5	Wheat, whole
Cootamundra	10.0	30 Dec	6	16 Mar	5	Barley, whole
Cummins	3.3	30 Apr	11	2 Nov	5	Barley, whole
Dalwallinu	2.5	15 Dec	5	1 Oct	6	Lupins/Barley
Ellinbank	22.6	1 Feb	5	25 Nov	5	Barley, whole
Esperance	3.5	1 Nov	5	2 Nov	5	Lupins/Barley
Goulburn	7.4	20 Nov	14	16 Nov	6	Wheat, whole
Hamilton	12.0	1 Jan	18	31 Dec	4	Barley, whole
Katanning	2.9	10 Feb	6	16 Jan	6	Lupins/Oats
Kyancutta	1.5	30 Apr	11	2 Nov	5	Barley, whole
Lake Grace	1.0	15 Mar	9	2 Nov	6	Lupins/Barley
Lameroo	2.2	1 Nov	6	2 Nov	6	Barley, whole
Launceston	13.6	31 Dec	16	2 May	5	Wheat, whole
Lucindale	8.1	1 Jan	7	16 Nov	5	Barley, whole
Mansfield	9.0	1 Jan	6	30 Nov	5	Barley, whole
Mt Barker	12.6	1 Dec	5	2 Feb	5	Lupins/Oats
Narrandera	7.5	1 Jan	8	16 Apr	5	Wheat, whole
Stawell	9.0	20 Feb	7	2 Dec	5	Wheat, whole
Swan Hill	3.2	2 Nov	7	2 Nov	5	Barley, whole
Tatura	7.4	20 Feb	7	2 Dec	5	Wheat, whole
Wellington	5.4	30 Apr	9	30 Nov	5	Wheat, whole

Table A11.10. Management of the steer enterprises at each of the 25 locations. S.R. = stocking rate in steers per hectare immediately after replacement. A “flexible” grazing management scheme was used in which animals were moved weekly to the paddock that would provide the highest rate of weight gain.

Location	Optimal Sustainable S.R.	Purchase Date	Purchase Age (months)	Purchase Weight (kg)	Earliest Steer Sale Date	Final Steer Sale Date	Target Steer Sale Weight (kg)	Maintenance Supplement
Armidale	1.26	1 Apr	8	206	1 Nov	15 Jan	420	Wheat, whole
Bakers Hill	1.45	1 Nov	7	275	1 Oct			Lupins/Oats
Birchip	1.24	1 May	8	180	1 Dec	1 Jan	400	Barley, whole
Colac	2.42	1 Dec	9	320	15 Oct	30 Nov	500	Barley, whole
Condobolin	0.34	1 Mar	9	242	15 Dec	15 Jan	400	Wheat, whole
Cootamundra	2.24	1 Apr	7	210	20 Dec	20 Jan	400	Barley, whole
Cummins	0.82	1 May	10	219	1 Nov	1 Dec	400	Barley, whole
Dalwallinu	0.51	1 Jan	10	278	1 Oct	1 Nov	400	Lupins/Barley
Ellinbank	3.97	1 May	9	243	1 Dec	28 Feb	450	Barley, whole
Esperance	0.81	15 Jan	9	287	1 Oct	1 Nov	420	Lupins/Barley
Goulburn	1.30	1 Mar	7	193	1 Dec	1 Jan	420	Wheat, whole
Hamilton	3.38	1 Jun	9	197	15 Dec	15 Jan	450	Barley, whole
Katanning	0.55	15 Nov	8	283	15 Oct	14 Nov	500	Lupins/Oats
Kyancutta	0.37	15 May	9	191	1 Dec	31 Dec	400	Barley, whole
Lake Grace	0.14	1 Jan	9	255	1 Dec			Lupins/Barley
Lameroo	0.48	15 Mar	8	220	15 Nov	15 Dec	420	Barley, whole
Launceston	3.18	1 Jun	9	251	1 Nov	31 Dec	400	Wheat, whole
Lucindale	2.01	1 Mar	8	236	1 Oct	15 Dec	420	Barley, whole
Mansfield	1.66	1 Feb	7	220	1 Oct	15 Jan	400	Barley, whole
Mt Barker	2.02	1 Jan	9	322	1 Oct	31 Dec	500	Lupins/Oats
Narrandera	1.74	1 Mar	8	242	15 Oct	15 Jan	420	Wheat, whole
Stawell	1.75	1 Apr	8	218	15 Nov	15 Jan	400	Wheat, whole
Swan Hill	0.90	15 Apr	8	173	15 Nov	15 Dec	420	Barley, whole
Tatura	1.60	1 Apr	7	196	1 Nov	31 Dec	400	Wheat, whole
Wellington	0.93	1 May	8	204	1 Nov	28 Feb	420	Wheat, whole

Table A11.11. Location- and paddock-specific values used in financial calculations. Property areas are used to convert the operator allowance to a per-hectare basis. Maintenance fertilizer cost per dry sheep equivalent for each location and paddock has been derived from the P requirements calculator of Cayley and Quigley (2005); the pasture class, soil loss factor and animal loss factor for each paddock are inputs to that calculation.

Location	Property Area (ha)	Replacement Cost ($/head)			Paddock	Pasture Class	Soil Loss Factor	Animal Loss Factor	P Fertilizer Requirement (kg P/DSE)
		Crossbred Ewe	Wether	Beef Cow					
Armidale	1100				1	Improved	Medium	Medium	1.06
					2	Poor	Medium	High	1.10
Bakers Hill	430				1	Improved	High	Low	1.05
					2	Improved	High	Low	1.05
Birchip	1300				1	Improved	Medium	Low	0.75
Colac	400				1	Improved	Medium	Low	0.88
Condobolin	1900				1	Improved	Low	Low	0.57
					2	Improved	Low	Low	0.57
Cootamundra	620				1	Improved	Medium	Low	0.86
Cummins	1200				1	Improved	Medium	Low	0.75
Dalwallinu	2100				1	Improved	High	Low	0.92
Ellinbank	400				1	Improved	Medium	Low	1.04
Esperance	1200				1	Improved	High	Low	1.00
Goulburn	750				1	Improved	Medium	Medium	1.00
Hamilton	430				1	Improved	Medium	Low	0.86
Katanning	1300				1	Improved	Medium	Low	0.78
Kyancutta	2600				1	Improved	Low	Low	0.52
Lake Grace	2500				1	Improved	High	Low	0.91
Lameroo	1800				1	Improved	Low	Low	0.55
					2	Improved	Low	Low	0.55
Launceston	570				1	Improved	Medium	Medium	0.99
Lucindale	650				1	Improved	Medium	Low	0.83

Location	Property Area (ha)	Replacement Cost ($/head)			Paddock	Pasture Class	Soil Loss Factor	Animal Loss Factor	P Fertilizer Requirement (kg P/DSE)
		Crossbred Ewe	Wether	Beef Cow					
Mansfield	770				1	Improved	Medium	Medium	1.04
Mansfield	500				2	Poor	Medium	High	1.08
Mount Barker	500				1	Improved	High	Medium	1.13
Narrandera	940				1	Improved	Low	Low	0.58
Stawell	810				1	Improved	Medium	Medium	0.96
					2	Improved	Medium	Medium	0.96
Swan Hill	2100				1	Improved	Low	Low	0.54
Tatura	1100				1	Improved	Low	Low	0.58
Wellington	1300				1	Improved	Medium	Low	0.72
					2	Improved	Medium	Medium	0.84
					3	Improved	Medium	High	0.95