Climatic Change

Climate change and broadacre livestock production across southern Australia. Adaptations by grassland management

--Manuscript Draft--

Manuscript Number:	CLIM-D-12-00515
Full Title:	Climate change and broadacre livestock production across southern Australia. Adaptations by grassland management
Article Type:	Research Article
Corresponding Author:	Afshin Ghahramani, Ph.D CSIRO Canberra, AUSTRALIA
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	CSIRO
Corresponding Author's Secondary Institution:	
First Author:	Afshin Ghahramani, Ph.D
First Author Secondary Information:	
Order of Authors:	Afshin Ghahramani, Ph.D
	Andrew Moore, Dr.
Order of Authors Secondary Information:	
Abstract:	Climate change has been predicted to cause a reduction in the productivity of grasslands. We have used the GRAZPLAN biophysical models to assess a range of pasture management practices as adaptation options under the SRES A2 global change scenario. The analysis spanned 4 dimensions: space (25 locations), time (2030- 2070), livestock enterprise (5), and management (4). Projection uncertainty was taken into account by considering climates from 4 GCMs. The effectiveness of adaptations varied widely among enterprises, locations, over time and under the 4 projected future climates. Increased soil fertility was the most effective option, if implemented over southern Australia as a whole, it was predicted to recover 127%, 109%, and 60% of the impact on gross income at 2030, 2050, and 2070, which return to historical period were predicted for high rainfall regions. Confinement feeding in summer and adding lucerne to the feedbase had an overall relative effectiveness of 58% and 23% in recovering income. Removing annual legumes in an attempt to preserve ground cover was ineffective in recovery of production decline. The effectiveness of these pasture-oriented adaptations tended to decrease over time as the impacts of climate change increased. For the majority of location x enterprise x years, individual incremental adaptations could partly recover the declines in income resulting from climate changes, and the most effective adaptation differed among locations. It appears unlikely that any single climate change adaptation to the feedbase of southern Australian livestock systems can return their profitability to historical levels of 1970-1999, at any location.
Suggested Reviewers:	Phil Thornton, Dr. CCAFS P.THORNTON@cgiar.org A internationally well known scientist in field of climate change and agricultural system
	Richard Eckard, Dr. The University of Melbourne richard.eckard@unimelb.edu.au Director of the Primary Industries Climate Challenges Centre, a joint research initiative between the University of Melbourne and the Victorian Department of Primary Industries

	Brendan Cullen, Dr. The University of Melbourne bcullen@unimelb.edu.au lecturer and scientist in the field of climate change impact and adaptation on agricultural system
	Nick Holden, Dr. UCD Dublin Nick.Holden@ucdc.ie Scientist in this field
	Kairsty Topp, Dr. SRUC, Scotland's Rural College kairsty.topp@sruc.ac.uk Scientist in this field
	Jean-François Soussana, Dr. INRA jean-francois.soussana@clermont.inra.fr Scientist in this field

Climate change and broadacre livestock production across southern Australia.

Adaptations by grassland management

Running title: Grassland management adaptations across southern Australia

Afshin Ghahramani*[1], Andrew D. Moore[1]

CSIRO Climate Adaptation National Research Flagship & Plant Industry

*Corresponding author: Afshin Ghahramani

Address: GPO Box 1600, Canberra ACT 2601, Australia

Tel: +61-2-624 64892, Fax: +61 2 6246 5166, Email: af.ghahramani@csiro.au

Key words: Pasture, feedbase, agricultural system, modelling, GRAZPLAN

Type of Paper: Original Research Article

For submission to Climatic change

Abstract

Climate change has been predicted to cause a reduction in the productivity of grasslands. We have used the GRAZPLAN biophysical models to assess a range of pasture management practices as adaptation options under the SRES A2 global change scenario. The analysis spanned 4 dimensions: space (25 locations), time (2030- 2070), livestock enterprise (5), and management (4). Projection uncertainty was taken into account by considering climates from 4 GCMs. The effectiveness of adaptations varied widely among enterprises, locations, over time and under the 4 projected future climates. Increased soil fertility was the most effective option, if implemented over southern Australia as a whole, it was predicted to recover 127%, 109%, and 60% of the impact on gross income at 2030, 2050, and 2070, which return to historical period were predicted for high rainfall regions. Confinement feeding in summer and adding lucerne to the feedbase had an overall relative effectiveness of 58% and 23% in recovering income. Removing annual legumes in an attempt to preserve ground cover was ineffective in recovery of production decline. The effectiveness of these pasture-oriented adaptations tended to decrease over time as the impacts of climate change increased. For the majority of location x enterprise x years, individual incremental adaptations could partly recover the declines in income resulting from climate changes, which the most effective adaptation differed among locations. It appears unlikely that any single climate change adaptation to the feedbase of southern Australian livestock systems can return their

profitability to historical levels of 1970-1999, at any location.

Introduction

Increased anthropogenic emissions of gases with greenhouse effects are expected to lead to changes in global climate patterns (Houghton et al., 2001) through significant increases in temperatures, which are predicted to cause changes in annual rainfall and its seasonal pattern (IPCC, 2007). Substantial changes in the climate are now highly likely to be unavoidable, and to date there are efforts have been done for mitigation of GHG, in some of developed countries, but so far are unlikely to be enough (Stafford Smith et al. 2011). Modelling studies indicate that climate changes will significantly affect the pasture and livestock industry through elevated atmospheric CO_2 concentration, changes in annual and seasonal rainfall and temperature during 2030 to 2070 (Cullen et al. 2009). In addition to declines in pasture production, the other main predicted challenges for grazing industry under climate change are decrease in forage quality, livestock heat stress, drought (Howden et al, 2007), and greater risk of soil erosion and degradation due to decline in ground cover. Reduction in the productivity of improved pastures of southern Australia (Cullen et al. 2009) will lead to a disproportionate decrease in the stocking rates that can be sustained owing to increased risk of low ground cover (Moore & Ghahramani, under review in Global Change Biology). Thus, strategies are required to maintain high levels of ground cover to maintain sustainable stocking rate. Livestock industry of southern Australia is 20% of the gross value of agricultural production in Australia (Moore et al. 2009). Because of the wide range of environments and livestock system practices there is a need for systematic evaluation of adaptation options across industry.

A number of review papers have proposed adaptation options that might permit stocking rates to be maintained under future climate change. These options include changes to grazing rotations, grazing times timing of reproduction, forage and animal genetics including the use of forage crops in mixed farming systems, reassessing fertilizer applications, and supplementary feeding (Adger et al., 2003; Howden et al., 2007).

While adaptation options have been suggested in the literature, there are rare studies that have quantified the effectiveness of these options in ameliorating the challenges, or exploiting the opportunities, posed by changing climates. Analyses of financial variability (Antle et al., 2004) and ecological system outputs are ways to explore impact of climate change and effectiveness of adaptation practices in livestock systems. Application of biophysical models have allowed for sophisticated simulations of future impacts and livestock system responses (Christensen et al. 2004). Therefore, modelling biophysical processes and interactions of pasture-animal in an agro-ecosystem frame are viable approaches to assess adaptation effectiveness on productivity of livestock industry under future climate change.

In this paper, by using the GRAZPLAN simulation models (Moore et al. 1997) we examine the potential of adaptations to livestock production systems to enhance the profitability and sustainability of livestock production across southern Australia under projected future climates. This area includes diverse environments which climate and pastures species might be similar to those all around the world e.g. new Zealand, South America, South Africa, southern Europe.

Methods

Simulation tools and model description

We applied the GRAZPLAN models (Moore et al. 1997; Freer et al, 1997), in order to simulate the above ground annual net primary productivity (ANPP, kg ha^{-1}) and profitability of livestock systems during a reference period and under future projected climate. We simulated pasture-livestock as a biophysical system including soil moisture, plant growth including plant response to CO_2 concentration, pasture management (Moore et al. 1997), ruminant feed intake, nutrition, and reproduction (Freer et al. 1997). Effects of increasing temperatures were accounted for by model equations describing effects 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). The livestock submodel included an equation for reductions in animal intakes on hot days (Freer et al. 1997). The soil moisture budget and infiltration were simulated based on the SWRRB model (Williams et al, 1985).

A set of 25 representative locations across temperate southern Australia was selected for analysis (Figure 2). Annual rainfall at the locations ranges between 299 and 1091 mm, with the seasonal pattern of rainfall ranging from highly winter-dominant to moderately summer-dominant. Mean annual temperatures varied between 11.6°C and 19.1°C during the historical reference period (1970 to 1999). At each location, a representative set of land resources (weather, soils and pastures) was described using the attributes required by the GRAZPLAN simulation models, and genotypes and management systems were specified for each of 5 livestock enterprises at each location: Merino ewes producing both fine wool and lambs for meat, Merino x Border Leicester cross ewes with an emphasis on lamb production, Angus cows producing yearling or weaner steers and heifers, Merino wethers for fine wool production, and Angus steers. 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 practices of 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.

Future climates at the years 2030, 2050 and 2070 were taken from projections for the SRES A2 scenario by 4 global circulation models (GCMs): CCSM3 (Collins et al. 2006), ECHAM5/MPI-OM (Roeckner *et al.* 2003), GFDL-CM2.1(Delworth et al. 2006) and HadGEM1 (Johns et al. 2006). Atmospheric CO_2 concentrations of 350 p.p.m for historical climate (1970-1999) and 451, 532 and 635 p.p.m for 2030, 2050, and 2070, respectively, were assumed. Projected climate results from each GCM were downscaled into daily weather data sequences using a technique adapted from that of Zhang (2007).

Adaptation options

Candidate adaptations for analysis were identified from literature reviews (e.g. Adger et al. 2003; Howden et al. 2007) and from changes to management suggested by livestock producers in workshops held by colleagues (our research was carried out within a larger program of research, development and extension). We chose 4 options from the resulting large set of possible adaptations, based on an initial assessment of their potential to reduce the frequency of low ground cover and on the frequency with which they were identified by producers in different regions of southern Australia. The 4 adaptation options selected for analysis were:

Higher soil fertility: increasing soil nutrient levels will increase plant growth, thus higher soil fertility should improve ground cover levels. Altering fertilizer usage is one of the most simple and technically feasible incremental adaptations; pasture growth will respond to changed fertilizer regimes immediately (Hill et al. 2004), and other responses will take place over a few years. “Fertility scalar”, a numeric value that represents the degree to which pasture growth will be restricted by soil fertility at times when soil water availability does not limit pasture growth. The initial values of the higher fertility scalar varied from location to location according to the local practices, on a 0-1 scale up to a maximum of 0.95 (A value of 1.0 indicates no such growth limitation). There will, however, a limitation for the highest fertility that soil can reach. We assumed this adaptation in two levels of 10% and 15%

increase of fertility by adding phosphorus fertilizer to the soil but if there were potential to allow us to more increase, then 20% of increase was applied. Level of increase was decided by expert opinion based on rainfall, soil type, and steepness of the paddock (Hill et al. 2004; Cayley and Quigley, 2005). Fertilizer cost in the model estimated as following

$$COST_{fert} = C_{phos} \sum_{p} PREQD_p \cdot \overline{DSE}_p \cdot AREA_p \tag{1}$$

where $COST_{fert}$ denotes to the cost of the P fertilizer required to maintain soil nutrient status, C_{phos} *assumed* \$5 /kgP as the cost of P fertilizer, $PREQD_p$ is the maintenance P requirement per DSE (Dry sheep equivalents) for paddock *p* calculated according to the method of Cayley and Quigley (2005), $\overline{DSE}_p$ is the average annual stocking rate in paddock *p* in DSE/ha, and $AREA_p$ is the area of paddock.

Confinement feeding: confinement feeding rules considered between 1 Dec and 31 Jul as an adaptation option to decrease pressure on pasture. Confinement feeding is placing animals in a feedlot during summer and autumn when pasture production is low. 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. There was no confinement feeding (or supplementary feeding) being considered for simulation during historical period.

Higher lucerne proportion: increasing lucerne proportion in pasture will be a suitable option because the shift of more rainfall to summer season has been predicted for future decades (Moore & Ghahramani, under review). Therefore, lucerne will potentially have more biomass production under future climate at summer seasons. In addition, it is reported that elevated atmospheric CO_2 concentration is likely to favour legumes over grasses in temperate pastures (e.g. Clark et al. 1997). Either 20% or 40% of land from the most-productive soil class separated into an extra paddock that contained a pure lucerne pasture. If the pastures at a location already included a lucerne component, the new lucerne paddock was in addition to the existing lucerne.

Removing annual Legume: Estimations, reported not only decrease in mean annual rainfall at semi arid areas (CSIRO and Australian Bureau of Meteorology 2007), but also increase in the frequency and intensity of the largest rainfall events (e.g. Lionello et al. 2002; Good et al. 2006). Thus, predicted low pasture coverage (Cullen et al. 2009), can potentially accelerate soil water erosion (also see Stokes and Howden 2010). Legume residues have weaker structure compared to grass species and so degrade more rapidly over summer, which can be expected to make soil erosion risk greater unless stocking rates are reduced to compensate (Moore & Ghahramani, under review). Managing pastures for lower legume content might therefore allow higher stocking rates in future climates, at the cost of reduced production per animal. The pasture in each modelled paddock modified to remove all of annual legumes other than lucerne.

A factorial simulation experiment was conducted in which the factors were climate scenario (1 + 4 x 3 levels), location (25), livestock enterprise (5), and adaptation option (4 at different levels). 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 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 presented at this “optimal sustainable stocking rate” (OSSR). For each year of the simulation run, an operating profit, OP ($/ha) was calculated as following

$$OP=INCOME-(COST_{var}+COST_{fert}+COST_{stock}+COST_{operator}) \qquad (2)$$

where $INCOME$ is the total income ($/ha) from meat and wool of the enterprise, $COST_{var}$ is the variable costs ($/ha) 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 ($/ha) of the P fertilizer required to maintain soil nutrient status, $COST_{stock}$ is the marginal capital cost of livestock ($/ha), and $COST_{operator}$ is an operator allowance (the equivalent cost of the farmer’s labour). Variable costs calculated using the same cost structure for each enterprise (and, where applicable, across enterprises).

The annual cost of phosphorus fertilizer in each simulation estimated from the maintenance P requirement for each paddock, calculated by Eq.1 as the long-term average dry sheep equivalents grazing the paddock using the approach of Cayley and Quigley (2005). The marginal cost of extra livestock accounted in the operating profit in order to make financial comparisons between different stocking rates more meaningful. This cost expressed relative to the capital cost of livestock at the sustainable optimal stocking rate for historical climate, and calculated as the product of a capital value per head and an interest rate (7%). A fixed operator allowance of $60,000 assumed for all locations and enterprises. In order to compare adaptation strategies across locations with different financial outputs, a relative “adaptation effectiveness” A_{ef} in compareto the histrorical period calculated as

$$A_{ef} = (A_P - N_A)/(H_P - N_A) \qquad (3)$$

where A_P denotes income after an adaptation, N_A is income without any adaptation, and H_P is income during the historical period. A_{ef} can also be calculated based on operational profitability ($/ha) obtained from Equation 2. See Moore and Ghahramani (under review in Global Change Biology) for more details of financial calculation In this paper, we estimated adaptation effetiveness in examined regions where climate change had negative effect on pasture and livestock production in compare to historical period of 1970-1999.

Results

Climate change effects on ANPP and profit

Average annual rainfalls differed widely among the four GCM projections. GFDL-CM2.1 showed the largest decrease of annual rainfall across the study area (10%, 11%, and 24% in 2030, 2050, and 2070 respectively), while 0%, 1% and 3% increases were projected by CCSM3 for 2030, 2050 and 2070. Annual mean temperature increased at similar rates under all examined GCMs; in average by 1.0°C, 1.5°C, and 2.4°C in 2030, 2050 and 2070. Modelled ANPP was highly variable among the GCM projections, with differences mainly determined by projected rainfall. Averaged over the 4 GCMs, ANPP of the study area decreased in the absence of adaptation by 10%, 8%, and 16% at 2030, 2050, and 2070 respectively. Under the climate projected by CCSM3, simulated average ANPP over southern Australia decreased by 3% at 2030 and then increased by 6% in 2050 and 2070; for GFDL-CM2.1, ANPP was estimated to decrease by 16% at 2030, 14% at 2050, and 28% at 2070. Western Australian locations tended to have larger decreases in estimated ANPP (e.g. at Lake Grace, the average decrease in ANPP estimated for 2070 by the four GCMs was 50%). Launceston (Tasmania) was exceptional: an increase in ANPP was predicted there under the HADGEM1 and CCSM3.0 projections.

In the absence of adaptations, modelled operating profits at OSSR decreased steadily under average effect of all GCMs from historical climate to 2070 for all locations except Launceston. When averaged over all locations and enterprises, operating profit decreased by 46%, 58%, and 72% at 2030, 2050, and 2070, respectively. The sharpest overall profit decline without adaptations was estimated under the GFDL-CM2.1 projection with 68%, 74% and 94% decreases in overall profitability at 2030, 2050, and 2070.

Effects of adaptations on ANPP, income and profit at 2030, 2050, and 2070

The specified increases in soil fertility resulted in a 17% increase in modelled long-term average ANPP over the study area when compared with no adaptation under the same projected climates. The proportional effect did not change between 2030, 2050 and 2070. Adoption of confinement feeding also increased modelled ANPP over the study area by 1-2% . Replacing existing pastures with pure lucerne stands decreased average ANPP over the study area by 3-4% , while removing annual legumes from the pastures decreased the spatial average ANPP by progressively greater amounts over time, reaching an 8% reduction by 2070 .

Adaptation effects on gross income differed widely among enterprises, locations, GCMs, and over time. Overall, higher soil fertility was the adaptation that produced the greatest increase in gross income (Table 1). This adaptation could return gross income to its historical level in high rainfall regions of the study area. Confinement feeding had the second largest overall effect on income, with adding lucerne to the feedbase in third place (Table 1). The adaptation effectiveness of the all simulated adaptations except lucerne decreased over time from 2030 to 2070 (Table 1).

Figure 1 shows changes in gross income relative to the historical period for no adaptation and after applying the 4 adaptations to each enterprise. Again, it can be seen that higher soil fertility has the greatest positive effect on gross income. At 2030, higher soil fertility is also the most successful option for ameliorating the impact of climate change at the worst-affected locations (the minimum and lowest-quartile income decreases are of larger magnitude than the corresponding values for other adaptation options). As a result, adopting higher fertility is more profitable than no adaptation – and hence more likely to be adopted – at a higher proportion of locations than confinement feeding. This explains why higher soil fertility is evaluated as more effective than confinement feeding in Table 1 even though the median changes in income in Figure 1 are higher at some enterprises or years for confinement feeding. The income advantage of higher soil fertility wears off over time, however by 2070, there are several locations for every enterprise at which none of the 4 adaptation options can prevent a collapse in gross income. Adoption of confinement feeding has much less effect on gross income at OSSR in the wether enterprise than in the other 4 enterprises. Adding lucerne to the feedbase has a similar but less pronounced tendency to reduce the variability between locations in the impact of climate change on income.

Figure 2 shows spatial and temporal changes in the relative effectiveness of each adaptation in the two most prevalent enterprises (Merino ewes and beef cattle). Figure 2 reveals that while higher soil fertility was effective at nearly all locations and times, its effectiveness was greatest and was maintained over time for the high-rainfall regions in eastern Australia. In low-rainfall regions, the initial relative effectiveness of higher soil fertility was smaller and it decreased over time. Confinement feeding was also more effective in high-rainfall regions for the Merino ewe and beef cattle enterprises, its relative effectiveness showed widespread increases over time (Figure 2). Adding lucerne to the feedbase had its greatest relative effectiveness in Western Australia at 2030. The relatively static overall effectiveness of this option masks a decrease in relative effectiveness in western regions and an increase in eastern regions, particularly for Merino ewes. Past 2030, removing annual legumes from the pastures was ineffective as a climate change adaptation to improve gross income at nearly all locations.

Variation and uncertainty of adaptation effect over time

Average annual rainfall and temperature are predicted to vary widely among downscaled GCMs across southern Australia, in which, variation of average relative change of GCMs to historical period increased over time (Figure 3). Winter rainfall decreased continuously from 2030 to 2070, which variability decreased from 2030 to 2050 and then increased toward 2070 (Figure 3b). Figure 3c shows that variation of mean annual temperature increases over time among GCMs across all location. The variations of simulation results for the *most effective adaptation* of examined enterprises are illustrated in Figure 4. Adaptation effectiveness (the most effective option that may vary over time) decreased over time in all enterprises. At 2030, in all enterprises, the best adaptation option is sufficient in more than half of the locations to return or even increase grazing systems to their 1970-1999 levels of financial output. Variability of effectiveness increased largely in steer enterprises at 2050, and slightly in Merino ewe, and was almost constant over time in Crossbred ewe, and wether enterprises. Only in beef cattle, there was tendency of increase in variability of the best adaptation effectiveness from 2030 to 2070 (Figure 4). At 2050 and 2070, the magnitude of climate change impacts on production generally becomes greater, and this decreased adaptation's recovery effect at the highly impacted locations (mostly at the dry margin of the cereal-livestock zone), therefore reductions in profitability remain even after adaptation of the grazing systems.

Uncertainty due to predicted climate

Adaptation effect differed widely among projected GCMs, demonstrating challenge to make decision on uncertainty of climate change impact and adaptation recovery capabilities. In

Merino ewe enterprises, for example, effectiveness was less variable among locations than variations among GCMs. Suggesting smaller spatial variability than variability among examined GCMs (Figure 5). At 2030, simulated effectiveness decreased from CCSM3.0 to ECHAM5/MPI-OM and then increased toward GFDL2.1 and HADGEM1 (Figure 5). Adaptation effectiveness declined over time in all GCMs and trend of difference between effectiveness under GFDL2.1 to HADGEM1 decreased over time because of increasing severe impact in HADGEM1 GCM (Figure 5). At 2030, pasture and livestock production were the highest under HADGEM1, but over time, effectiveness simulated to be highly variable under HADGEM1, despite the less and decreasing variability of the annual rainfall under this GCM, may suggesting spatial changes in the other factors other than annual rainfall (e.g., changes in rainfall seasonal pattern, temperature, etc). Over time, not only recovery effect of adaptations decreased but also variability and uncertainty predicted to increase (Figure 5). Figure 6 shows how effectiveness of adaptation options varied among GCMs in Merino ewe enterprises (as example among enterprises). Confinement feeding had the greatest variability of effectiveness among adaptation options across southern Australia under all GCMs and focused years. The second most variable adaptation was increased soil fertility. Adding lucerne and removing legume options were the less variable (and less effective) options under all GCMs and at all focus years.

Discussion

The best adaptation option

Increased soil fertility (which mainly achieved by adding phosphorus) was the most effective of the 4 adaptation options. In average across all southern Australia, only this adaptation could effectively increase ANPP. Confinement feeding adaptation was more effective in high rainfall regions, most likely because of a lower frequency of dry periods, and spatial variation of its effectiveness increased with time (Figure 1) due to severe climate impact on dry cereal-livestock zone. However, over time the importance (among adaptations) of the confinement feeding option increased, even with exacerbated climate change effect (e.g. Merino ewe enterprises in Table S1). Adding lucerne to the feedbase appeared to be a partly effective strategy for low rainfall regions. ANPP under the "zero annual legume" adaptation became progressively less than under no adaptation from 2030 to 2070. This suggests that even under future climates, the higher nutritive value of legumes may outweigh the disadvantage of more rapid ground cover loss. As explained above, increased soil fertility was the most feasible option specially for earlier decades of the century but it would better to be associated with confinement feeding and lucerne adaptations, particularly at later decades.

For second half of the century, the most part of the Livestock industry and in particular, lower-rainfall parts of the cereal-livestock zone will require different adaptations than feed base options, e.g. combination of options, transformational adaptations, new technology, a complete re-thinking of the feedbase, or sustained price increases in order for livestock production to remain viable. As an example of a particular enterprise, Table S1 (supplementary material) shows how the best effective adaptation option varied among locations and over time in the Merino ewe enterprises. However, to apply an adaptation at farm scale, not only effectiveness value but also direction of other factors such as socio-economical parameters can contribute in farmer decision to select best adaptation option. It is essential to keep all stakeholders and policy makers connected and informed of adaptation strategies and their feasibilities in order to a practical implementation of designed strategies.

Uncertainty of adaptation effects

Variation often gives rise to uncertainty (Lindley, 2006) and produces uncertainty because we are not certain how variable factors will drive system responses. Here, we qualitatively assess variations of livestock system output (income) under different GCMs and over time to see how different are the responses of modelled livestock enterprises. Rainfall, temperature, and CO_2 are the main controlling climate factors of pasture and livestock systems that are predicted to change during future decades. The effectiveness of adaptation options varied widely among the dimensions of time and climate projections. Time scale is a critical factor in analysis of vulnerability and adaptation effectiveness (Patt et al., 2005), because of uncertainty in start point of major changes (e.g. drought) and different direction of changes predicted by climate scenarios over time. Current methods for projecting and validating evaluations of future capacities, sensitivities, and responses on the basis of present patterns of resource distribution are associated with high degree of uncertainties, making difficulties for decision makers (Patt et al. 2005). Production and income influenced by disease, soil erosion, extreme events, etc can be assumed to be controllable but still can add uncertainty to the assessments. On the other hand, climate change may provide opportunities as adaptation processes occur simultaneously (Eakin and Luers, 2006). Crimp et al. (2010) reported possible slight increase in Muarray-Darling Basin livestock industry under climate change within our examined area. Our simulated results shown positive impact of climate change at few regions in southern Australia as well (Figure 2), however this effect is also associated with uncertainty because of different directions of GCMs.

As pointed out by O’Brien and Leichenko, 2000, adaptations, will not be isolated from other probable decisions and management practices made by farmers or the other decision makers. Outputs of the livestock system will be result of synergies among all biophysical and socio-economical factors and it would not be simple to separate trade-offs of individual practices. Currently, quantification of self-adaptation (Pannell, 2010) and historical improvements effect has not been included in assessments of adaptation strategies (e.g., historical plant and animal genetic improvement). These will increase adaptability of industry to the climate change and we will address parts of this in the next paper of these series of publications. In addition, there are economical and ecological benefits in recovering depletion of income in livestock system while sustaining high vegetation cover e.g. control soil erosion, land degradation, and water quality, etc, and this cannot easily be expressed in the market values.

Barriers

Producers are potentially be able to provide supplementary feeding material from their own farm. But in addition to the international food supply concern, if the grain price ratio to the meat / wool shifts upward, then confinement feeding will become less viable option. Increased lucerne proportion option, can be limited by the soil characteristics, e.g. acidic soil or waterlog. Increased soil fertility (the most effective adaptation in this research) by addition of phosphorus will need further consideration on its availability. Currently there is limitation of high-quality, highly accessible phosphate rock availability for producing fertilizers, which, this limitation constraining by additional economical, social and ecological factors (Cordell, 2010). Estimates of globally available remaining phosphate rock reserves are varied between

60 to 130 years (e.g. Steen, 1998) which 90% of all phosphate demand is for agricultural fertilizer (Schroder et al. 2010). It is predicted that the rate of global demand and production of high-grade phosphate rock will increase by world population to reach a peak point by 2030 as inflection point of supply (Cordell et al. 2009). As we predicted here, year 2030, was the most effective focus year of increased fertility adaptation. In case of southern Australia, we will need 60 kt of phosphorous or about 144 kt of (P_2O_5) to reach the fertility level that is about 0.24% of global production in 2009 (Cordell, 2009). This is 22% of Australian consumption in 2009 which was 641 kt (ABARES, 2011) that is still less than peak P_2O_5 consumption of 1187 kt in 2001. However, addition of this fertilizer can be done gradually over a designed range of time, say 5 years, and then considering phosphorous life cycle (Simpson et al. 2011), producers will need to keep P level for maintenance purposes. It is essential to make sure and minimize the potential environmental impacts of phosphorus which its loss from agricultural system to water bodies can cause eutrophication, decline in water quality, landscape quality, etc (Schroder et al. 2010). Geopolitical issues also can restrict the availability of phosphate because there is a great imbalance in global distribution of phosphate sources (Schroder et al. 2010).

Conclusions

It is likely that in 2030, examined pasture and feeding incremental adaptations can return most livestock systems to profitability of reference period of 1970-1999. By 2050 and 2070, our findings suggest that the most part of the southern Australian Livestock industry and in particular, lower-rainfall parts of the cereal-livestock zone will require either combination of adaptation, transformational adaptations, new technology, a complete re-thinking of the feedbase, or sustained price increases in order for livestock production to remain viable. We suggest that adaptation options may change over time at some locations, but it is always essential to estimate changing risk at farm scale in order to make decision for selection of the best effective option.

Acknowledgments

This research was supported by funding from the Australian Government Department of Agriculture, Fisheries, and Forestry under its Climate Change Research Program; Meat & Livestock Australia; Dairy Australia; and Australian Wool Innovation.

References

ABARES 2011, Agricultural commodity statistics 2011, December, Canberra.

Adger NW, Huq S, Brown K, Conway D, and Hulme M (2003) Adaptation to climate change in the developing world, *Progress in Development Studies*, **3**, 179–195.

Antle JM, Capalbo SM, Elliot ET, Paustian KH (2004) Adaptation, spatial heterogeneity and the vulnerability of agricultural systems to climate change and CO2 fertilization: an integrated assessment approach.Clim. Change 64:289–315.

Cayley J, Quigley PE (2005) *Phosphorus for sheep and beef pastures*. Victorian Department of Primary Industries, Hamilton, Victoria.

Clark H, Newton PCD, Bell CC, Glasgow EM (1997). Dry matter yield, leaf growth and population dynamics in Lolium perenne Trifolium repens-dominated pasture turves exposed to two levels of elevated CO_2. *Journal of Applied Ecology* 34, 304-316.

Christensen L, Coughenour MB, Ellis JE, Chen ZZ (2004) Vulnerability of the Asian typical steppe to grazing and climate change. Clim. Change 63:351–56.

CSIRO and Australian Bureau of Meteorology (2007) Climate change in Australia: technical report 2007. CSIRO and Australian Bureau of Meteorology, Melbourne.

Cullen BR, Johnson IR, Eckard R J, Lodge GM, Walker RG, Rawnsley RP, McCaskill MR (2009) Climate change effects on pasture systems in south-eastern Australia. *Crop & Pasture Science* 60, 933-942.

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.

Collins WD, Bitz CM, Blackmon ML, *et al.* (2006) The Community Climate System Model version 3 (CCSM3). *Journal of Climate* **19**, 2122-2143. doi: 10.1175/JCLI3761.1.

Cordell D, Drangert JO, White S (2009) The story of phosphorus: global food security and food for thought. Global Environmental Change19, 292–305.

Cordell D. (2010) The Story of Phosphorus: Sustainability implications of global phosphorus scarcity for food security, Thesis. Department of Water and Environmental Studies, Linköping University, Sweden.

Delworth TL, Broccoli AJ, Rosati A, *et al.* (2006) GFDL's CM2 global coupled climate models. Part I: formulation and simulation characteristics. *Journal of Climate* 19, 643-674. doi: 10.1175/JCLI3629.1.

Eakin H, Luers AL. 2006. Assessing the vulnerability of social-environmental systems. Annu. Rev. Environ. Resour. 31:365–94.

Hill JO, Simpson RJ, Graham P, Moore AD, Chapman DF (2004) Impact of phosphorus application and sheep grazing on the botanical composition of sown and naturalized native grass pastures. *Australian Journal of Agricultural Research* 55, 1213-1225.

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (2001) Climate Change 2001. The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, UK.

Howden SM, Soussana JF, Tubiello FN, Chhetri N, Dunlop M, Meinke H (2007) Adapting agriculture to climate change. Proc Natl Acad Sci U S A 104(50): 19691-19696.

Ghahramani A, Moore AD (2012) Increasing soil fertility and altering legume-grass balance as adaptation strategies for sustainable livestock production under climate change. Edited by I. Yunusa. Proceedings of 16th Australian Agronomy Conference, Armidale, NSW.

IPCC (2007) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Lindley DV (2006) Understanding uncertainty. Wiley, Hoboken. DOI: 10.1002/0470055480

Long SP, Ainsworth EA, Rogers A, Ort DR (2004) Rising atmospheric carbon dioxide: plants FACE the future. Annual Review of Plant Biology 55, 591–628. doi: 10.1146/annurev.arplant.55.031903.141610

Johns TC, Durman CF, Banks HT, *et al.* (2006) The new Hadley Centre Climate Model (HadGEM1): Evaluation of coupled simulations. *Journal of Climate* **19**, 1327-1353. doi: 10.1175/JCLI3712.1.

Moore AD, Donnelly JR, Freer M (1997) GRAZPLAN: decision support systems for Australian grazing enterprises. III. Growth and soil moisture submodels, and the GrassGro DSS. Agricultural Systems 55, 535–582. doi: 10.1016/S0308-521X(97)00023-1.

Moore AD, Bell LW, Revell DK (2009) Feed gaps in mixed farming systems: insights from the Grain & Graze program. *Animal Production Science* **49**, 736-748. doi: 10.1071/AN09010.

Moore AD, Ghahramani A (under review in Global change Biology) Climate change and broadacre livestock production across southern Australia. 1. Impacts of climate change on pasture and livestock productivity, and on sustainable levels of profitability.

O'Brien KL, Leichenko RM (2000) Double exposure: assessing the impacts of climate change within the context of economic globalisation. Global Environmental Change 10, 221–232.

Pannell DJ (2010) Policy for climate change adaptation in agriculture. In 'Paper presented at the 54th Annual Conference of the Australian Agricultural and Resource Economics Society'. Adelaide, 10–12 February 2010.

Patt A, Klein RJT, de la Vega-Leinert A (2005) Taking the uncertainty in climatechange vulnerability assessment seriously. Comptes Rendus Geosci. 337:411–24.

Roeckner E, Bäuml G, Bonaventura L, *et al.* (2003) The atmospheric general circulation model ECHAM5. Part I: Model description. Max Planck Institute for Meteorology Report 349. Max Planck Institute for Meteorology, Hamburg. 127pp.

Schröder M, Cordell D, Smit AL, Rosmarin A (2010) Sustainable Use of Phosphorus. Report 357, Plant Research International, part of Wageningen UR, The Netherlands.

Simpson RJ, Oberson A, Culvenor RA, Ryan MH, Veneklaas EJ, Lambers H, Lynch JP, Ryan PR, Delhaize E, Smith FA, Smith SE, Harvey PR, Richardson AE (2011) Strategies and agronomic interventions to improve the phosphorus-use efficiency of farming systems. Plant Soil 349(1–2):89–120.

Stafford Smith M, Horrocks L, Harvey A, Hamilton C (2011) "Rethinking adaptation for a 4 degrees C world." Philos Transact A Math Phys Eng Sci 369(1934): 196-216.

Steen I (1998) Phosphorus availability in 21st century: management of a non-renewable resource. Phosphorus and Potassium 217:25-31.

Stokes C J and Howden S M (2010). Adapting Agriculture to Climate Change: Preparing Australian Agriculture, Forestry and Fisheries for the Future. Melbourne: CSIRO Publishing.

Williams J R, Nicks A D, Arnold J G (1985) Simulator for water resources in rural basins. Journal of Hydraulic engineering. 111, 970-986.

Zhang XC (2007) A comparison of explicit and implicit spatial downscaling of GCM output for soil erosion and crop production assessments. *Climatic Change* 84, 337-363.

Figure caption

Figure 1: Boxplots showing the relative change of *income* ($/ha)at the optimal sustainable stocking rate from the historical baseline to 2030, 2050, and 2070 for five livestock enterprises, for grazing systems in which a range of climate change adaptation options have been implemented. Each boxplot shows the variation of income change across 25 locations, after averaging over the climates predicted by 4 GCMs. Unlike Table 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 is the same as for the historical period.

Figure 2: Effectiveness of adaptations (from Eq.3) in Merino ewe and beef cattle enterprises in recovering the impact of climate change on gross income across southern Australia (0.0 = no benefit; 1.0 = a return to the 1970-99 baseline value of income, and >1 means higher income than the historical period). Adaptations were applied whether or not they increased income at the sustainable optimum stocking rate. Values are averages over 4 GCMs. Regions shown in grey were estimated to have higher gross income per hectare under climate change than under historical climate without adaptation. This will give opportunity to increase production by implementing practices that in the

negatively affected regions are called adaptation.

Figure 3: Variation of relative change in compare with historical period (a) annual rainfall, (b) winter rainfall, (c) annul temperature under mean effect of four examined GCMs across Southern Australia.

Figure 4: Variation in effectiveness of the best adaptations (based on annual *income*) on 5 livestock enterprises over time at locations where climate change will have negative effect across southern Australia under projected future climates. Effectiveness values are averages over 4 GCMs and are given as changes relative to annual income of 1970-1999 period, calculated by equation 2. 0 = no benefit; 1 = a return to the 1970-99 baseline value of production.

Figure 5: (a) Variation of relative changes in annual rainfall with comparing to the historical period, among GCMs at 2030, 2050 and 2070. (b) Variation of relative effectiveness of *the most effective* adaptation at Merino ewe enterprises across southern Australia among four GCMs at 2030, 2050 and 2070.

Figure 6: Variation of relative effectiveness of simulated *income* over time and among adaptation options and GCMs in Merino ewe enterprises.

Table 1. Relative effectiveness of simulated adaptations in recovering the impact of climate change on the total value of livestock production (*income*) 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 four GCMs over all locations and five livestock enterprises.

Adaptation	2030	2050	2070
Higher soil fertility	1.27	1.09	0.60
Confinement feeding	0.80	0.69	0.26
Adding lucerne to the feedbase	0.23	0.26	0.20
Zero annual legumes	0.05	0.01	0.00

Figure 1
Click here to download high resolution image

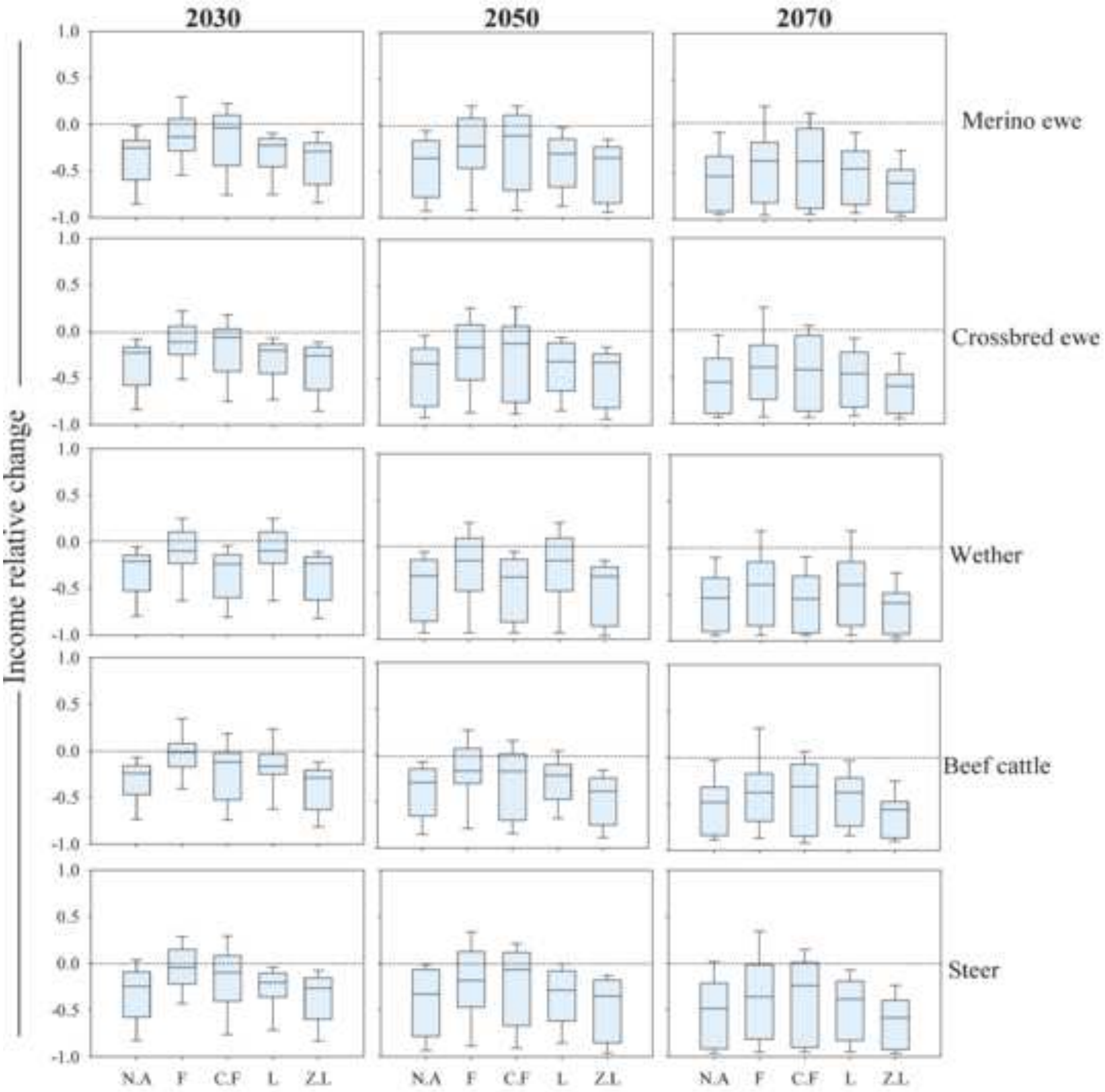

Figure 2

Click here to download high resolution image

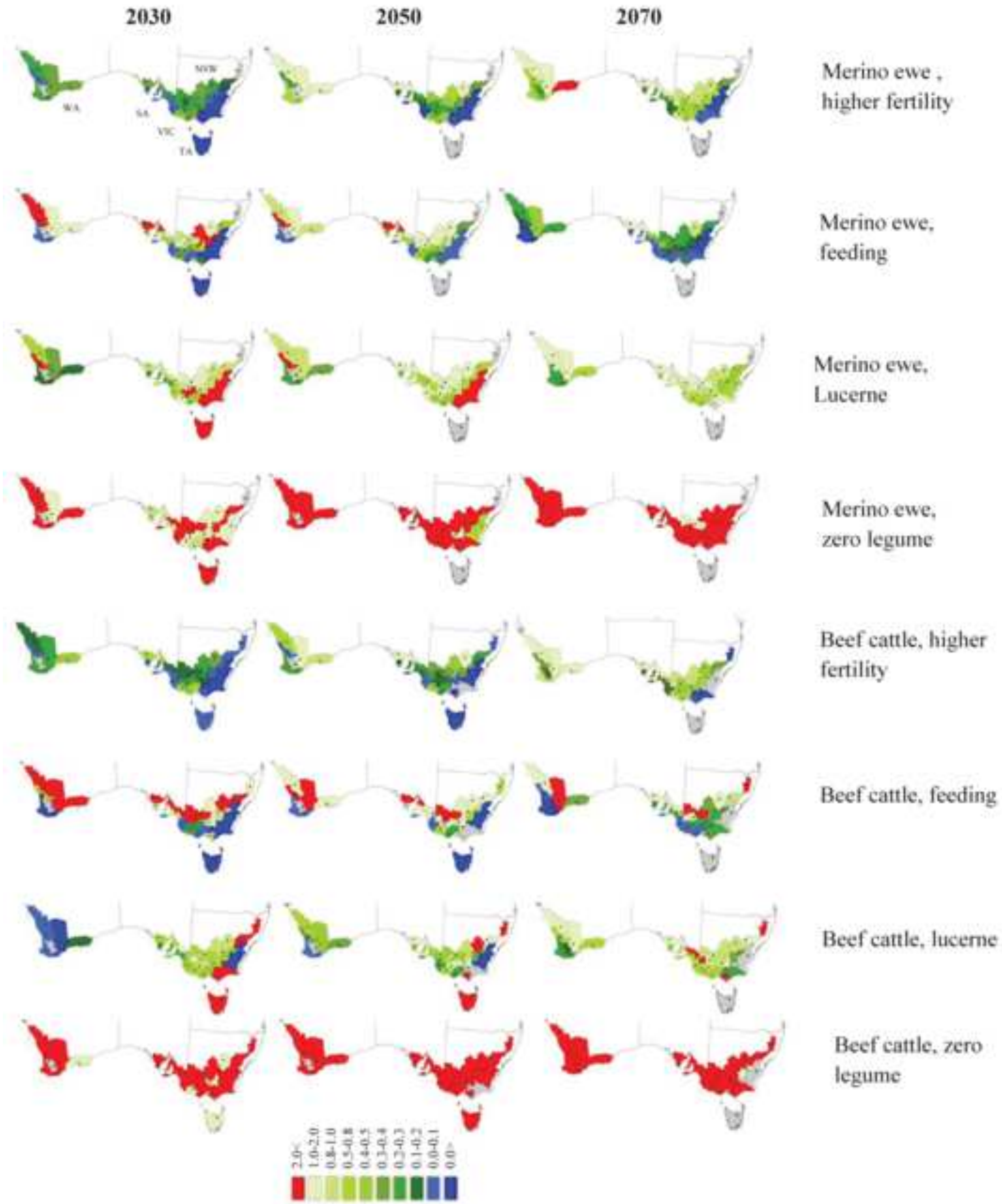

Figure 3
Click here to download high resolution image

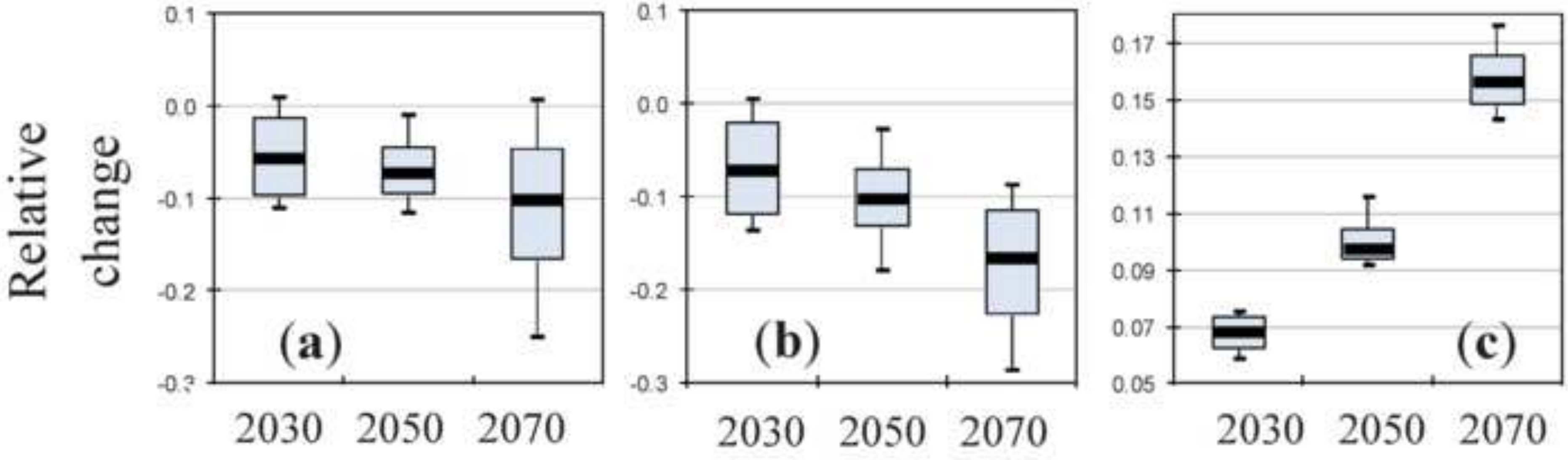

Figure 4

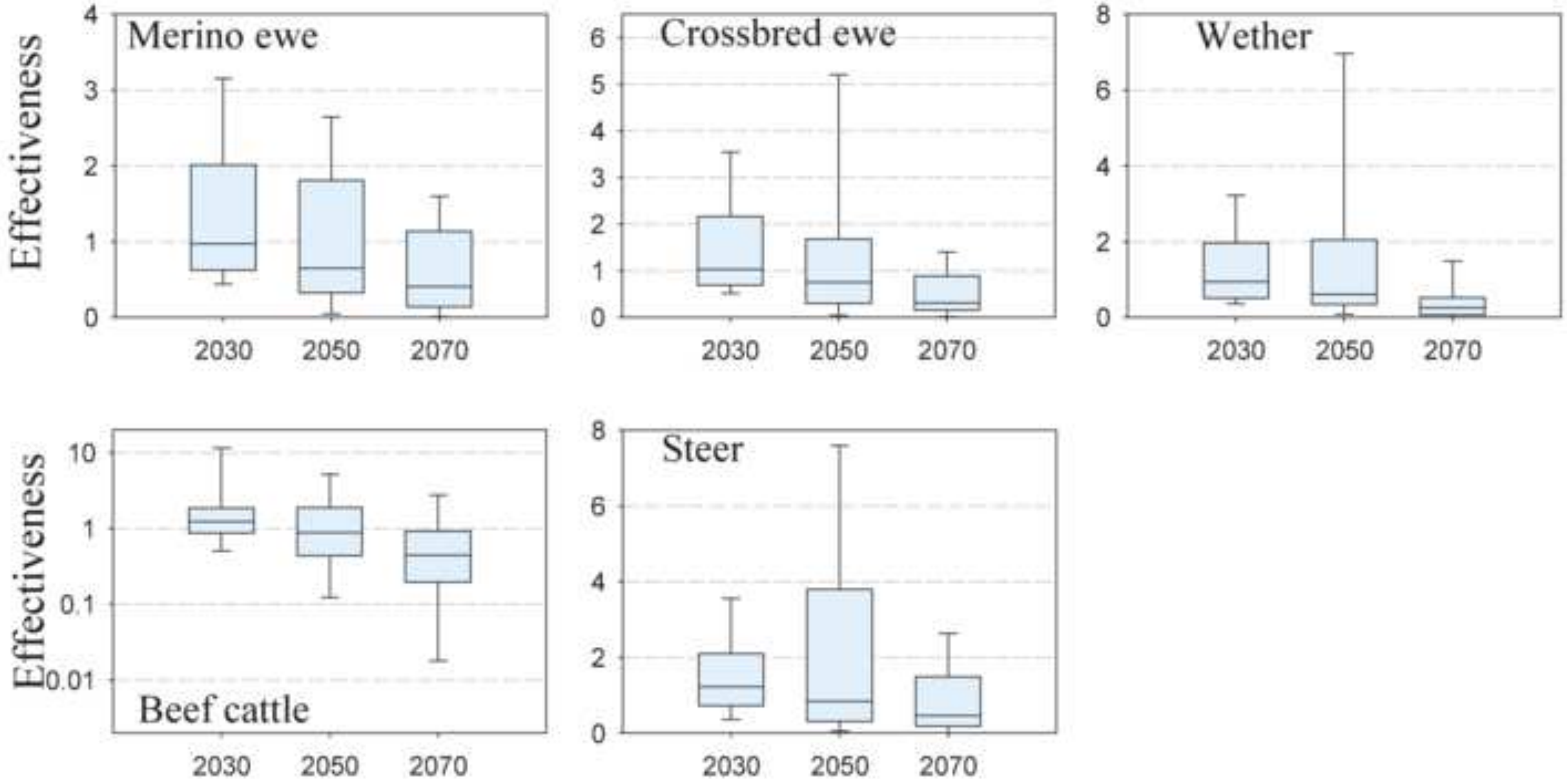
Merino ewe
Effectiveness
0
1
2
3
4
2030
2050
2070
Crossbred ewe
0
1
2
3
4
5
6
2030
2050
2070
Wether
0
2
4
6
8
2030
2050
2070
Beef cattle
Effectiveness
0.01
0.1
1
10
2030
2050
2070
Steer
0
2
4
6
8
2030
2050
2070

Figure 5

Click here to download high resolution image

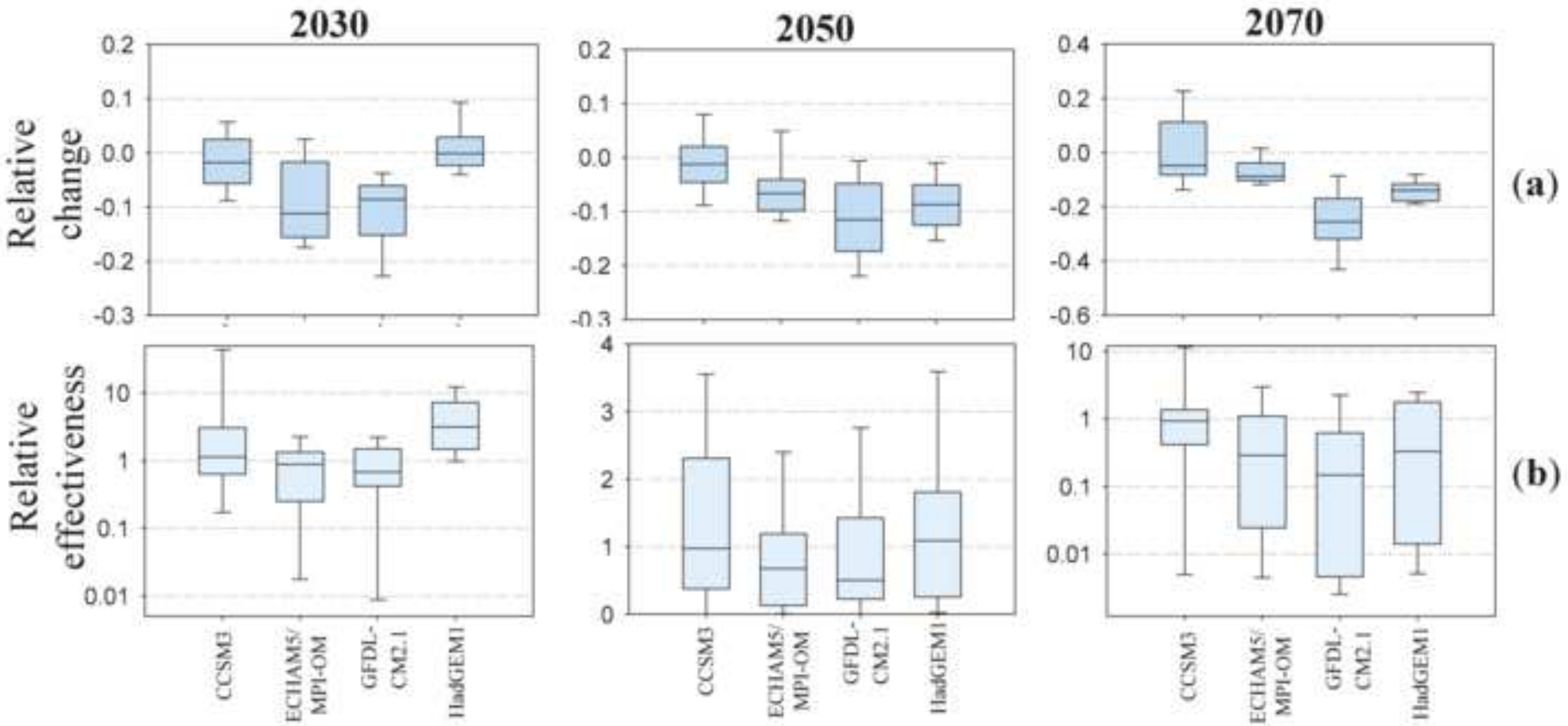

Figure 6

Click here to download high resolution image