

Climate change and broadacre livestock production across southern Australia. 3. Adaptation options via livestock genetic improvement

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Abstract. Climate change is predicted to reduce the productivity of the broadacre livestock industries across southern Australia; to date there has been no formal evaluation of the potential of genetic improvement in cattle or sheep to ameliorate the impacts of changing climates. We used the GRAZPLAN simulation models to assess selection of five traits of sheep and cattle as adaptation options under the SRES A2 global change scenario. Analysis of the breeding strategies was carried out for 25 representative locations, five livestock enterprises and three future years (2030, 2050, 2070). Uncertainty in future climates was taken into account by considering projected climates from four global circulation models. For three sheep enterprises, breeding for greater fleece growth (at constant body size) was predicted to produce the greatest improvements in forage conversion efficiency, and so it was the most effective genetic adaptation option. For beef cow and steer enterprises, breeding for larger body size was most effective; for beef cows, however, this conclusion relied on per-animal costs (including provision of bulls) remaining stable as body size increases. Increased conception rates proved to be less effective but potentially viable as an adaptation in beef cow and crossbred ewe enterprises. In the southern Australian environments that were analysed, our modelling suggests that breeding for tolerance to heat stress is unlikely to improve the performance of livestock production systems even at 2070. Genetic improvement of livestock was able to recover much less of the impact of climate change on profitability at drier locations where the need for adaptation is likely to be greatest. Combinations of feedbase and livestock genetic adaptations are likely to complement one another as the former alter the amount of forage that can be consumed, while the latter affect the efficiency with which consumed forage is converted to animal products. Climate change impacts on pasture production across southern Australia are likely to have only small effects on methane emissions intensity, as are a range of candidate genetic and feedbase adaptations to climate change; methane emissions per hectare in future climates will therefore be driven mainly by changes in livestock numbers due to alterations in pasture productivity.

Additional keywords: breeding, grazing systems, modelling.

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Introduction

The broadacre sheep and beef cattle industries in the high-rainfall and cereal–livestock zones of southern Australia together account for ~20% of the nation's gross value of agricultural production (Australian Bureau of Statistics 2012). Anthropogenic emissions of greenhouse gases, along with other human-induced changes to the earth system, are expected to cause substantial changes in the climate of the farms that produce these livestock in coming decades; for example, projections reported by CSIRO (2007a) for 2050 indicate a warming of ~0.8–2.8°C and decreases in rainfall of 0–20%.

In the first paper of this series (Moore and Ghahramani 2013) we used simulation modelling to show that these climate changes will adversely impact pasture growth and livestock production across most of southern Australia. For the

SRES A2 scenario of global change (IPCC 2000) and in the absence of adaptations other than adjusting stocking rates to avoid excessive erosion risk, we estimated that total aboveground net primary productivity would decrease by an average of 9% in 2030, 7% in 2050 and 14% in 2070 from historical levels. We found, however, that the sustainable rates of pasture utilisation would decrease disproportionately, so that projected decreases in operating profit averaged 27% in 2030, 32% in 2050 and 48% in 2070. The proportional reductions in both pasture growth and profitability were greater at locations near the dry margin of the cereal–livestock zone. A second paper (Ghahramani and Moore 2013) explored a range of adaptation options that aimed to alter the amount or pattern of forage supply, or to increase the proportion of forage production that could be safely utilised; we found that increasing soil fertility and (where feasible) the incorporation of lucerne into the

feedbase were the most effective adaptations, and that the effectiveness of adaptations tended to be lower in the drier parts of the cereal–livestock zone.

Genetic improvement of sheep to suit Australian conditions has been under way since the early days of European settlement, but until the 1970s breeding of southern Australian beef cattle followed a British lead (Pattie 1973). The introduction of index-based selection methods in the 1980s and their subsequent improvement has led to accelerating genetic progress in participating beef cattle seedstock herds, especially for the Angus breed (Barwick and Henzell 2005) and for terminal sire sheep breeds (Swan *et al.* 2009). Rates of gain in Merino sheep in recent years have been slower (Swan *et al.* 2009). The extent to which these genetic improvements in stud animals are reflected in the wider herd and flock is difficult to ascertain from the literature.

Discussion of livestock genetics as an adaptation to climate change in Australia (Howden *et al.* 2008; Stokes *et al.* 2010) has focussed mainly on breeding for adaptation to heat stress, primarily for sheep and cattle in the pastoral zone. However, a wide range of genetic improvements – those that improve the efficiency with which livestock convert forage to animal product – are also potentially viable adaptations to the reductions in forage supply that can be expected under future climates. Modern approaches to livestock improvement that are based on quantitative genetics can deliver substantial gains in production per head in commercial flocks and herds (Johnston 2007; Swan *et al.* 2009).

To date there has been no formal evaluation of the potential of genetic improvement in cattle or sheep to ameliorate the impacts of changing climates, either in Australia or elsewhere. In this paper, therefore, we extend the climate change impacts analysis of Moore and Ghahramani (2013) to examine the potential of livestock genetic improvements to adapt sheep and beef cattle production systems across southern Australia to projected future climates. This analysis is a companion to that in Ghahramani and Moore (2013); in particular, we address the effects of single genetic adaptations in isolation, leaving combination of adaptation approaches to the final paper in the series.

Simulation modelling is the only viable way to integrate the multiple, and spatially variable, effects of changing climate on pasture and animal production with the physiological changes and tradeoffs implied by alternative breeding objectives. We have therefore carried out this climate change adaptation study with the GRAZPLAN simulation models of pasture and livestock systems (Freer *et al.* 1997; Moore *et al.* 1997).

Methods

The modelling study reported here extends work reported in companion papers (Ghahramani and Moore 2013; Moore and Ghahramani 2013) that have used similar methods; readers are referred to these papers for further detail.

The GRAZPLAN models

The GRAZPLAN simulation models of the dynamics of grazed temperate grasslands were used for this analysis. These models operate at a daily timestep and consist of a water balance model

(Moore *et al.* 1997), a pasture growth model (Moore *et al.* 1997) and a model of the intake, nutrition, reproduction and mortality of ruminants (updated from that reported in Freer *et al.* 1997). These biophysical models are coupled to a flexible representation of the management of grazing systems (Moore *et al.* 1997). Moore and Ghahramani (2013) provide an account of the wide variety of physical and physiological responses to changing climates that are captured in the GRAZPLAN water balance and pasture model. The ruminant model is based on the Australian feeding standard (CSIRO 2007b). It includes direct effects of increased temperature via 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); the last of these effects will also be modified by changes in rainfall during the period that lambs are born. Methane production in the model is predicted with an equation derived from that of Blaxter and Clapperton (1965), in which the proportion of gross energy intake lost as methane varies between 0.06 and 0.09 with the metabolisable energy (ME) content of the diet and the energy balance of livestock.

In common with many biological simulation models, the genetic characteristics of livestock are represented in the ruminant model by a set of 256 ‘genotypic parameters’. A hypothetical livestock genotype can be described by modifying these parameters, and the effect of introducing it into a given livestock production system can then be simulated. Tradeoffs in animal performance due to limited supplies of energy and protein will be accounted for within these simulations.

Variation of the effects of adaptations across space, time and livestock enterprises

The study area (henceforth ‘southern Australia’) is an area of 1.00 million km² (Fig. 1); it includes 0.33 million km² of grazed lands that support 84% of Australia’s sheep production and 36% of its beef cattle production by value (Australian Bureau of Statistics 2012). Climates and soil types vary widely; for example, annual rainfall at the locations modelled in this study varies from 299 to 1091 mm and mean annual temperature from 11.6 to 19.1°C (Table 1). Forage types are consequently very diverse (Pearson *et al.* 1997). Projected climate changes also vary across the study area (Christensen *et al.* 2007). To capture the likely geographic differences in the effectiveness of different adaptations, we have used a set of 25 representative locations (Fig. 1; Table 1) that were identified using methods described by Moore and Ghahramani (2013). At each of the 25 locations, a representative set of land resources (weather, soils and pastures) was described using the attributes required by the GRAZPLAN simulation models (Moore and Ghahramani 2013; Table 1).

Climate projections from the CMIP3 global climate models were used in this study. In order to take account of the uncertainty in projected climates, climate projections from four global circulation models (GCMs) were considered for each future year: CCSM3 (Collins *et al.* 2006), ECHAM5/MPI-OM (Roeckner *et al.* 2003), GFDL-CM2.1 (Delworth *et al.* 2006) and UKMO-HadGEM1 (Johns *et al.* 2006). GCMs were selected on the basis of their overall skill over the Australian continent (CSIRO 2007a) and the availability of the monthly-scale projected weather data required for downscaling. A single

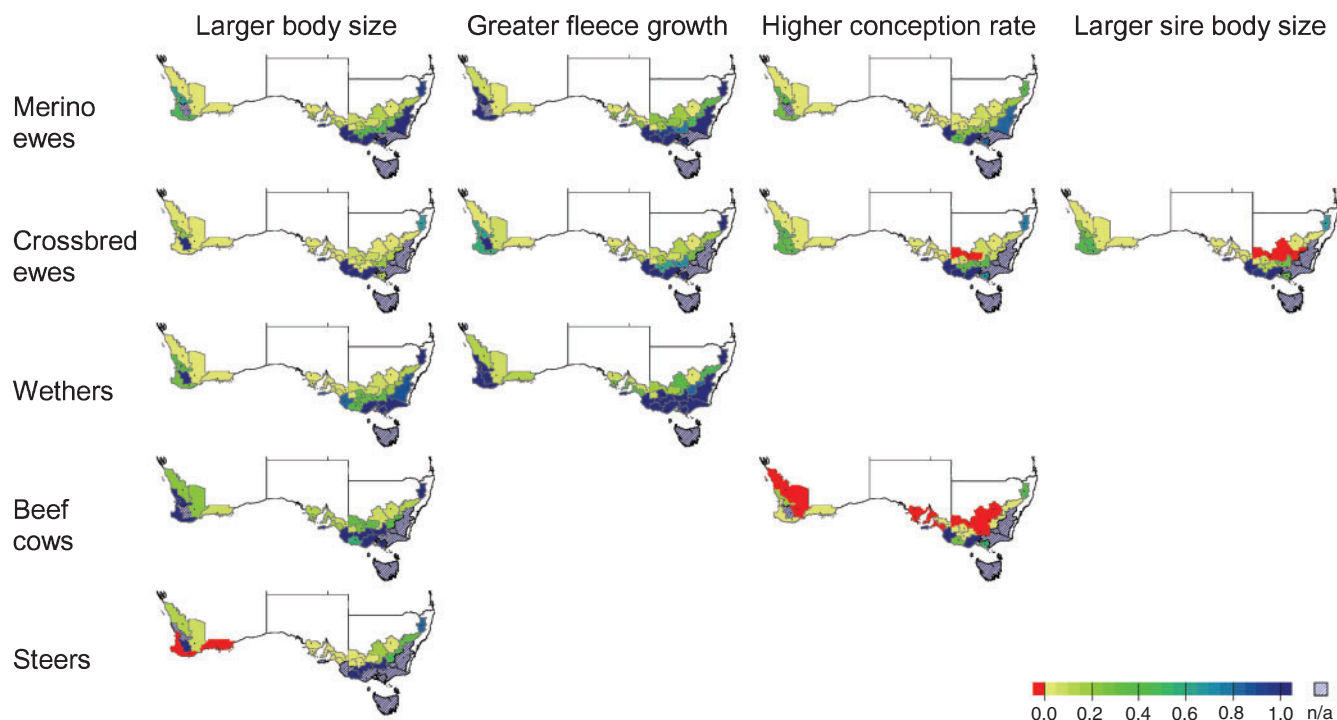


Fig. 1. Spatial variation in the relative effectiveness of five simulated genetic adaptations in recovering the impact of climate change on operating profit for each livestock enterprise to which they can be applied. A value of 0.0 indicates no benefit from the best adaptation, and a value of 1.0 indicates a return to the 1970–99 baseline value of production. Adaptations were applied to all location \times enterprise combinations. Operating profits have been averaged across four global circulation models before calculation of relative effectiveness values.

future emissions scenario was used; the high-emissions SRES A2 scenario was selected because it is consistent with recent history (Peters *et al.* 2012). A reference period of historical weather data (1970–99) was simulated (with an atmospheric CO₂ concentration of 350 ppm), plus projected future climates for the years 2030, 2050 and 2070 with CO₂ concentrations of 451, 532 and 635 ppm, respectively (Houghton *et al.* 2001).

Historical daily weather data sequences for each location were taken from the Patched Point dataset (Jeffrey *et al.* 2001). Weather data for each projected climate were constructed using a downscaling technique modified from that of Zhang (2007; for details of the modifications see Moore and Ghahramani 2013). This algorithm was selected because it accounts for changes in precipitation (in particular) at three temporal scales that are important in pasture–livestock systems: inter-annual, between seasons and also the short-term patterns of wet and dry days.

Livestock production systems were specified for each of five enterprises: Merino ewes producing both fine wool and lambs for meat, Merino \times 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 were assumed across all locations (Table 3) in order to facilitate comparisons across sites. The same genotypic parameters were used for the Merino ewe and Merino wether enterprises and for the Angus cow and Angus steer enterprises. Representative 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 \times location combination. Details of the livestock management systems can be found in Tables S1 and S2, available as Supplementary Material to this paper.

Adaptation options

As used in this paper, ‘forage conversion efficiency’ is the ratio of gross income from meat and wool to mass of pasture dry matter consumed, expressed in \$/kg. In terms of the water-use efficiency framework of Moore *et al.* (2011), it is computed as.

$$FCE = f_{9,meat} \times f_{10,meat} + f_{9,wool} \times f_{10,wool} \quad (1)$$

where f_9 denotes the conversion efficiency of pasture to a livestock product and f_{10} denotes the price of the product.

Several possible adaptations through improved livestock genetics were designed and examined, on the premise that using animals with higher conversion efficiency would mitigate the consequences of a lower amount of consumable pasture growth. There are numerous possible routes to more feed-efficient livestock: the ones modelled here were chosen because they were nominated by livestock producers in a series of workshops (Pattinson 2011).

Higher body size

Maintenance energy requirements of ruminants vary with the 3/4 power of bodyweight, while their maximum rate of intake increases roughly linearly (CSIRO 2007b). Larger

Table 1. Representative locations at which grazing systems were modelled, with their climate, soils and pastures

Climate statistics are for the period 1970–99. ‘Clover’ denotes *Trifolium subterraneum* unless otherwise specified. The ‘Stubbles?’ column indicates whether the forage base included crop residues during summer. Aboveground net primary productivity (ANPP) values are for the Merino ewe enterprise at its optimal sustainable stocking rate under the historical reference (1970–99) climate

Location	State	Latitude and longitude	Annual rainfall (mm)	Annual mean temperature (°C)	ANPP (t/ha)	Stubbles?	Threshold frequency cover <0.70	Proportion of area	Soil description	Pasture
Armidale	NSW	30°31'S, 151°40'E	778	13.9	6.5	N	0.10	0.5	Prairie soil	Phalaris–annual grass–clover
Bakers Hill	WA	31°46'S, 116°29'E	594	17.3	10.5	Y	0.07	0.5	Lateritic podzol	Native pasture (<i>Bothriochloa</i>)
Birchip	Vic.	35°59'S, 142°55'E	403	15.6	5.0	Y	0.18	0.8	Deep sand	Annual grass–clover
Colac	Vic.	38°17'S, 143°40'E	699	13.8	12.4	N	0.07	0.2	Deep sand	Lucerne–perennial ryegrass–annual grass
Condobolin	NSW	33°04'S, 147°14'E	470	17.2	3.8	Y	0.20	1.0	Clay loam	Barley grass–annual medic
								1.0	Gradational clay	Perennial ryegrass–clover–annual grass
Cootamundra	NSW	34°38'S, 148°01'E	671	15.4	8.9	Y	0.07	0.8	Red brown earth	Barley grass–annual medic
Cummins	SA	34°16'S, 135°44'E	408	16.3	5.3	Y	0.11	0.2	Red brown earth	Lucerne–barley grass–annual medic
Dalwallinu	WA	30°17'S, 116°40'E	366	19.1	4.1	Y	0.17	1.0	Duplex soil	Phalaris–annual grass–clover
Ellinbank	Vic.	38°15'S, 145°56'E	1091	13.6	14.4	N	0.30	1.0	Clayey red brown earth	Barley grass–annual medic
Esperance	WA	33°36'S, 121°47'E	507	16.4	6.7	Y	0.07	1.0	Red clay	Annual grass–clover
Goulburn	NSW	34°49'S, 149°44'E	668	13.1	6.9	N	0.08	1.0	Red Ferosol	Perennial ryegrass–white clover
Hamilton	Vic.	37°39'S, 142°04'E	663	13.2	11.0	N	0.07	1.0	Deep sandy duplex	Annual ryegrass–clover
								1.0	Shallow yellow–grey duplex	Phalaris–annual grass–clover
								1.0	Silty clay loam over clay	Perennial ryegrass–clover–annual grass
Katanning	WA	33°41'S, 117°33'E	471	15.9	6.3	Y	0.08	1.0	Sandy duplex	Annual ryegrass–clover
Kyancutta	SA	33°08'S, 135°33'E	299	17.2	3.3	Y	0.27	1.0	Grey calcareous sandy loam	Barley grass–annual medic
Lake Grace	WA	33°06'S, 118°28'E	352	16.8	3.1	Y	0.21	1.0	Yellow shallow sandy duplex	Annual ryegrass–clover
Lameroo	SA	35°20'S, 140°31'E	386	16.0	4.1	Y	0.18	0.5	Sandy loam over poorly structured brown clay	Barley grass–annual medic
Launceston	Tas.	41°32'S, 147°12'E	641	11.6	8.3	N	0.07	0.5	Sandy loam over brown clay	Barley grass–annual medic
Lucindale	SA	36°58'S, 140°22'E	588	14.8	8.1	N	0.07	1.0	Shallow duplex	Perennial ryegrass–clover–annual grass
Mansfield	Vic.	37°03'S, 146°05'E	735	13.7	7.8	N	0.07	1.0	Sandy loam on clay loam	Phalaris–clover
Mt Barker	WA	34°38'S, 117°38'E	693	15.0	10.8	N	0.07	0.6	Deep yellow–grey duplex	Phalaris–clover–annual grass
Narrandera	NSW	34°45'S, 146°33'E	485	16.5	7.1	Y	0.13	0.4	Deep yellow–grey duplex	Native pasture (<i>Microlaena</i>)
Stawell	Vic.	37°04'S, 142°47'E	574	14.1	8.0	Y	0.07	1.0	Loamy sand over medium clay	Annual ryegrass–clover
								0.6	Red duplex	Annual ryegrass–clover
								0.6	Fine sandy clay loam over heavy clay	Annual ryegrass–clover
								0.4	Fine sandy clay loam over heavy clay	Phalaris–annual ryegrass–clover
Swan Hill	Vic.	35°20'S, 143°33'E	379	16.5	4.0	Y	0.23	1.0	Sandy clay loam	Barley grass–clover
Tatura	Vic.	36°26'S, 145°16'E	488	14.8	6.8	Y	0.13	1.0	Sandy loam over clay loam	Barley grass–clover
Wellington	NSW	32°30'S, 148°58'E	610	16.7	5.9	Y	0.11	0.2	Sandy clay loam over clay	Lucerne–annual grass
								0.5	Sandy clay loam over clay	Phalaris–annual grass–clover
								0.3	Red duplex	Native pasture (<i>Bothriochloa</i>)

animals should therefore use a smaller proportion of the energy in consumed forage for maintenance, leaving more energy for growth, wool production or reproduction. There has been a long-standing trend of increasing livestock body size in Australia; Bell and Moore (2012) noted that the weight of ewes sold for mutton in Australia has increased by 9% in the last 30 years. The body size of an animal breed is represented in the GRAZPLAN ruminant model by a parameter called the 'standard reference weight', i.e. the weight of a mature, empty female in average body condition.

Higher fleece weight

There is considerable variation in potential wool growth rates, both between and within sheep breeds (e.g. Atkins 1980). Animals that devote a higher proportion of their energy and protein intake to wool growth can be expected to generate more profit per kilogram of forage eaten, as long as the resources devoted to extra wool growth do not compromise survival or reproduction. Breeding programs that aim to increase fleece weights typically achieve this aim in part through an increase in the body size of livestock; here, however, we consider an increase in fleece weight that is obtained at a constant body size. In the GRAZPLAN ruminant model, this increase is modelled as a change in the ratio of a parameter known as the 'reference fleece weight' to the standard reference weight.

Higher conception rates

In ewe and beef cow enterprises, a higher reproduction rate will result in a greater energetic efficiency in the flock or herd as a whole, because it increases the proportion of young, growing livestock. 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 in overall reproduction rates therefore lies in fecundity and in post-natal survival in sheep. We have focussed on fecundity as an adaptation option, as it applies to both sheep and cattle enterprises. In both sheep and cattle, most of any conception rate increase will have to appear as an increase in the proportion of multiple births; this carries a risk of increased peri-natal mortalities of offspring (Donnelly 1984). In the GRAZPLAN ruminant model, conception rate per oestrus cycle is controlled by a set of nine genotypic parameters that describe the effect of time of year and of relative body size for single, twin and triplet conceptions (Freer *et al.* 1997).

Higher body size of sires

This adaptation option is limited to livestock enterprises where terminal sires are used (here, only the crossbred ewe enterprise). By using a breed of rams with larger body size, the offspring will be larger, thereby increasing the conversion efficiency both of individual young stock and of the production system as a whole. The usefulness of this management option is limited by the risk of dystokia; if fetuses grow too large relative to their mothers, birth becomes difficult and the death rate of lambs or calves increases (Woolliams *et al.* 1983). The effect of sire body size is represented in the GRAZPLAN ruminant

model by assuming that the genotypic parameters describing offspring can be obtained by averaging those in the maternal and paternal genotypes.

Improved tolerance to heat stress

At high temperatures, livestock can reduce their food intake (Weston 2002) and sustained high temperatures during mating can reduce fertility (Amundson *et al.* 2006). Modelling of the heat balance of livestock (e.g. Howden and Turnpenny 1997) is made difficult by a lack of knowledge of behavioural adaptations, in particular shifts in the timing of grazing within the day. In the GRAZPLAN ruminant model, potential intake of livestock is reduced linearly once maximum temperature exceeds a threshold, but only when minimum temperatures are also high (Freer *et al.* 1997).

One genetic adaptation that we did not consider was breeding for fleeces with lower fibre diameter. Finer wool receives higher prices, and so breeding for it is a viable strategy for individual producers. Here, however, we consider adaptations that receive widespread adoption, and if the Merino industry as a whole moves to finer wool, then over the decades the price premium is likely to dissipate.

Modelling the adaptations

A key difference between genetic adaptations and the feedbase and livestock management adaptations considered in earlier papers in this series is that the former need to be implemented slowly over time. In other words, we needed to consider gradual improvement of genetics over time, using rates of progress that should be achievable given our knowledge of rates of genetic improvement during the last 20–30 years. We assumed linear rates of genetic gain over time and used selection index theory (Falconer 1981) to place the projected rates of genetic progress for the adaptations (other than heat stress tolerance) on a common basis. Relevant genetic variances and correlations for four traits (adult bodyweight, greasy fleece weight, fibre diameter and conception rate, i.e. offspring born per mother mated; Table 2) were sourced from the literature for the two sheep breeds and for Angus cattle. Fibre diameter was included as we assumed that it would be maintained over time. Selection indices were constructed for higher body size (i.e. equal proportional changes in weight and fleece weight, zero change in fibre diameter and fertility), higher fleece weight (change in fleece weight only) and higher conception rate (change in conception rate only) and rates of genetic gain per unit of selection intensity were calculated from the genetic parameters. A common selection intensity was then chosen that gave a relative rate of increase in body size of Merino sheep of 0.5% in the first year; the corresponding rates of genetic gain calculated for the other traits and breeds are given in Table 3.

Little or no information is available about the genetic control of heat stress in sheep or cattle, and so the scope for genetic improvement through heat stress was evaluated by modelling alternative genotypes with zero effect of heat stress on intake. Effects of increased temperature on reproduction were neglected, as mating times in the representative management systems generally avoided this

Table 2. Information used to estimate consistent rates of genetic gain

Values are sourced from Safari *et al.* (2005, 2007a, 2007b) for sheep and from Jeyaruban *et al.* (2009) and Gregory *et al.* (1997) for cattle. CV denotes coefficient of variation; the four traits considered are mature body size (*SRW*), conception rate of mature females (*CR*), reference fleece weight of mature sheep (*SFW*) and reference fibre diameter of mature sheep (*FD*). Genetic correlations are given above the diagonal in the right-hand part of the table, phenotypic correlations are given below the diagonal and heritabilities are given (in bold) on the diagonal

Livestock breed	Trait	Phenotypic CV	Genotypic CV	Correlations and heritabilities			
				<i>SRW</i>	<i>CR</i>	<i>SFW</i>	<i>FD</i>
Merino sheep	<i>SRW</i>	0.12	0.045	0.38	0.38	0.20	0.15
	<i>CR</i>	0.63	0.034	0.12	0.05	-0.26	0.02
	<i>SFW</i>	0.16	0.066	0.36	-0.17	0.42	0.29
	<i>FD</i>	0.07	0.051	0.16	-0.06	0.24	0.68
Border Leicester sheep	<i>SRW</i>	0.06	0.018	0.30	0.38	0.20	0.15
	<i>CR</i>	0.53	0.053	0.12	0.10	-0.26	0.02
	<i>SFW</i>	0.21	0.106	0.36	-0.17	0.51	0.29
	<i>FD</i>	0.07	0.041	0.36	-0.06	0.24	0.57
Angus cattle	<i>SRW</i>	0.13	0.062	0.49	0.31	-	-
	<i>CR</i>	0.21	0.019	0.26	0.09	-	-

Table 3. Genotypic parameters used to estimate the effectiveness of individual genetic improvements as adaptations to climate change

Names of genotypic parameters are the same as in Table 2. Values are computed from the information in Table 2 using selection index theory, as described in the text. Initial conception rates are long-term values for mature females in average body condition, averaged over the 25 locations for the standard environmental conditions, pastures and livestock management and at the historical optimal sustainable stocking rate

Livestock breed	Trait	Units	Initial value	Relative gain in first year	2030	2050	2070
Merino sheep	<i>SRW</i>	kg	50.0	0.0050	55.0	60.0	65.0
	<i>CR</i>	-	1.24	0.0040	1.32	1.40	1.48
	<i>SFW</i>	kg	5.00	0.0064	5.64	6.28	6.92
Border Leicester sheep	<i>SRW</i>	kg	60.0	0.0035	64.2	68.4	72.6
	<i>CR</i>	-	1.39	0.0051	1.49	1.59	1.70
	<i>SFW</i>	kg	5.00	0.0089	5.89	6.78	7.67
Angus cattle	<i>SRW</i>	kg	500.0	0.0065	565.0	630.0	695.0
	<i>CR</i>	-	0.95	0.0022	0.99	1.03	1.08

risk; temperature-humidity indices during mating reached sustained levels likely to induce stress (Amundson *et al.* 2006; Marai *et al.* 2007) only for the sheep enterprises at Dalwallinu at 2050 and 2070.

Simulation experiment

As for our analysis of feedbase adaptation options (Ghahramani and Moore 2013), a factorial simulation experiment was conducted in which the factors were climate scenario (1 + 4 × 3 levels), location (25), livestock enterprise (5), and genetic adaptation option (5). Historical-climate simulations were run over the years 1970–99, while projected-climate simulations were run over 30 years of climate realisations for the nominated future year. For each combination of the factors, a range of stocking rates was modelled and physical and financial outputs from the grazing system were stored from each simulation run. In particular, modelled long-term average methane emissions on a per-hectare basis were recorded for each simulation, as well as for the simulations of feedbase

adaptation options reported in Ghahramani and Moore (2013). 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 at each stocking rate with a 7% interest rate (Moore and Ghahramani 2013). Costs and prices were computed from average values over the years 2007–11. A fixed operator allowance of \$60 000 was assumed for all locations and enterprises, but it was spread over varying farm areas. Because we were analysing scenarios in which adoption of improved genetics was widespread across the industry, we assumed that market competition between studs would prevent relative increases in the price of rams and bulls.

An 'optimal sustainable stocking rate' (OSSR) was selected for each location × enterprise × climate × adaptation combination as that which gave highest profit while keeping the frequency of low ground cover (defined as cover <0.70) below location-specific thresholds (Table 1). All results are reported at the OSSR for a given climate, location, enterprise and adaptation scenario.

In order to compare adaptation strategies across locations and enterprises with different financial outcomes, we computed the 'relative effectiveness' of an adaptation as the proportion of the negative impact of climate change that it recovers:

$$RE = (P_A - P_N)/(P_H - P_N) \quad (2)$$

where P_A denotes long-term average operating profit under a projected climate when an adaptation has been implemented, P_N is operating profit under that climate without any adaptation, and P_H is operating profit during the historical period. The relative effectiveness of a given increase in profitability will, by definition, be larger at locations where the impact of climate change on profitability is smaller; in circumstances where $P_N \geq P_H$, the relative effectiveness cannot be calculated. System-level efficiency measures from the framework of Moore *et al.* (2011) were also computed from the biophysical and economic simulation results, in order to gain insight into ways that genetic improvements resulted in more economically viable production systems.

Results

Profitability changes due to the genetic adaptations were much more consistent between GCMs than for the feedbase adaptations reported by Ghahramani and Moore (2013). All results are therefore reported as averages over the GCMs.

Industry-level effectiveness of genetic adaptations for each livestock enterprise

Table 4 shows the changes over time in the relative effectiveness of the different genetic adaptations in restoring profitability of each livestock enterprise, when averaged over the study area. At

this industry scale, greater fleece growth was clearly the most effective option for the three sheep enterprises, while selection for larger body size was most effective for the cattle enterprises. Larger body size was of intermediate relative effectiveness in the three sheep enterprises, as was higher conception rate in the crossbred ewe and beef cow enterprises. Apart from tolerance to heat stress, which was not modelled as an incremental improvement, the relative effectiveness of all the genetic adaptations increased from 2030 to 2050 and then declined from 2050 to 2070.

For some specific adaptation \times enterprise combinations, (greater fleece growth for wethers and larger body size for beef cows and steers), the modelled rates of genetic progress were sufficient to restore average operating profit per hectare to or beyond its historical level. Because most of the adaptations were applicable to only a subset of the enterprises, however, the overall relative effectiveness of each adaptation in restoring the profitability of broadacre livestock production was diluted: the highest industry-level relative effectiveness was 0.59 for greater fleece growth at 2050.

The modelled relative effectiveness of complete tolerance of high temperatures as an adaptation was very small for all enterprises and future years: the highest effectiveness found for this adaptation option (0.02 for steers at 2030) was below the lowest value for all the other adaptations (0.06 for higher conception rate in beef cows at 2030). Adaptation to heat stress is therefore not considered further in these results.

Regional variations in the effectiveness of genetic adaptations

The spatial patterns of the relative effectiveness of each genetic adaptation are shown in Fig. 1 for 2050, the future year at which the effectiveness of genetic adaptation was greatest. It can be

Table 4. Relative effectiveness of five simulated genetic adaptations in recovering the impact of climate change on average operating profit for each of five livestock enterprises across southern Australia (0.0 = no benefit; 1.0 = a return to the 1970–99 baseline value of operating profit)

Adaptations were only applied to location \times enterprise combinations where they increased profit at the sustainable optimum stocking rate. Average operating profits have been computed across 25 locations (weighted by area of grazed land) and four global circulation models before calculation of relative effectiveness values

Adaptation	Year	Merino ewe	Crossbred ewe	Wether	Beef cow	Steer	All enterprises
Larger body size	2030	0.28	0.20	0.25	0.52	0.48	0.33
	2050	0.32	0.26	0.31	1.16	0.99	0.47
	2070	0.23	0.13	0.22	0.64	0.55	0.30
Greater fleece growth	2030	0.48	0.40	0.95	–	–	0.35
	2050	0.68	0.71	1.34	–	–	0.59
	2070	0.48	0.42	1.01	–	–	0.38
Higher conception rate	2030	0.12	0.23	–	0.06	–	0.12
	2050	0.17	0.33	–	0.45	–	0.23
	2070	0.12	0.18	–	0.33	–	0.16
Larger sire body size	2030	–	0.16	–	–	–	0.04
	2050	–	0.21	–	–	–	0.05
	2070	–	0.10	–	–	–	0.03
No heat stress	2030	0.00	0.01	0.01	0.01	0.02	0.01
	2050	0.00	0.00	0.01	0.02	0.01	0.01
	2070	0.00	0.01	0.00	0.02	0.01	0.01

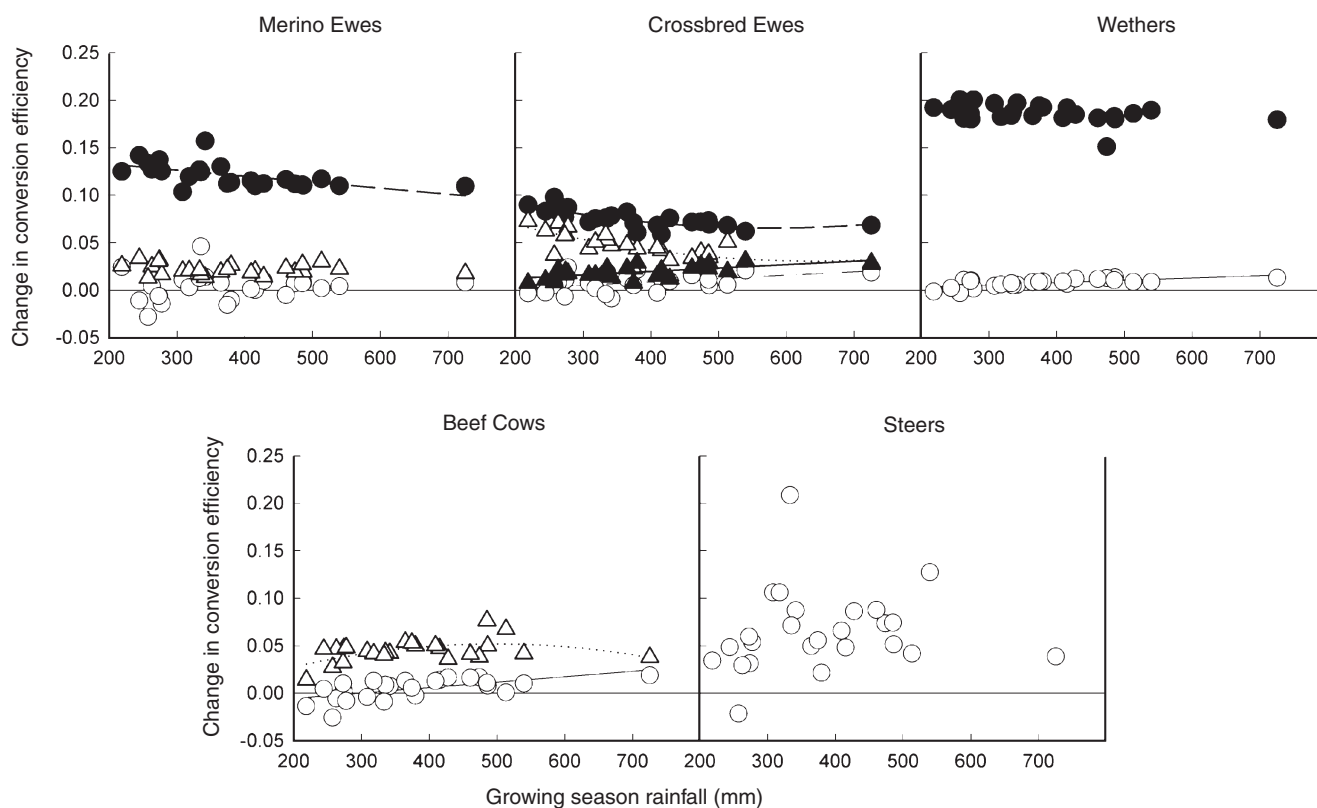


Fig. 2. Genetic improvement, climate, and the conversion of consumed forage into livestock products under projected climates across southern Australia in 2050. Each point shows the proportional change in conversion efficiency at a location brought about by a genetic adaptation to climate change, using no adaptation as a reference: larger body size (○), greater fleece growth (●), higher conception (△), and higher sire body size (▲). Conversion efficiencies are computed as dollars of gross income per kg of forage DM consumed and are averages over four global circulation models. Linear or polynomial regressions on growing season (April–October) rainfall are shown where they are significant.

that the different genetic adaptations did, however, alter the forage conversion efficiencies of the livestock production systems. Breeding for greater fleece growth had the largest overall effects on conversion efficiency, with the gains in conversion efficiency being slightly greater at low-rainfall locations in the ewe enterprises. In the Merino ewe and wether enterprises, the increases in forage conversion efficiency from breeding for greater fleece growth were much greater for the other adaptations. For the crossbred ewe enterprise, however, especially at lower-rainfall locations, the differences between the conversion efficiency gains from breeding for greater fleece growth and breeding for higher conception rate were much smaller and so the most-effective adaptations for this enterprise might alter if the ratio of sheep meat price to wool price were to increase above its 2007–11 level. Breeding for higher conception rate was estimated to increase conversion efficiency of the beef cattle enterprises by a greater amount than breeding for larger body size, even though the changes in profit due to higher conception rate were smaller. In keeping with their relative effectiveness (Table 4), higher conception rate produced greater increases in conversion efficiency in the crossbred ewe enterprise than in the Merino ewe enterprise. Larger body sizes increased forage conversion efficiency of steer enterprises by as much as 20%, but with a good deal of idiosyncratic variability between locations. In the other

enterprises – including beef cattle – breeding for larger body size only had small effects on conversion efficiency, generally with larger increases at wetter locations.

Changes in methane emissions under projected climates and adaptations

As can be seen from Table 6, modelled methane emissions per hectare fall significantly over the study area under projected future climates, but this is driven almost entirely by reductions in OSSR (Moore and Ghahramani 2013); emissions intensity changes relatively little except in the steer enterprise, where it declines by 4% at 2070. The additional changes in methane emissions per hectare from adapting via livestock genetic improvement are small, but emissions per dollar of income decline in response to these adaptations, especially to breeding for greater fleece growth (which produces the greatest increase in conversion efficiency). For three of the feedbase options examined by Ghahramani and Moore (2013), methane emissions respond differently: adding lucerne to the feedbase, higher soil fertility and the use of confinement feeding all increase OSSR and hence methane emissions per hectare while having little effect on methane emissions intensity. Removing annual legumes from pastures, which is generally an unprofitable option, also increases methane emitted per dollar earned.

Table 6. Modelled changes in methane emissions and emissions intensity from five livestock enterprises across southern Australia under projected climates at 2030, 2050 and 2070

The first part of the table shows modelled proportional changes in methane emissions (in kg CH₄/ha) and the emissions intensity of livestock production (in kg CH₄/\$ gross income) from each of five enterprises under projected future climates, using historical climate as a reference. The second part of the table shows the modelled proportional changes in methane emissions and emissions intensity resulting from the adoption of each of nine adaptations to climate change, using the no-adaptation case under projected future climate as a reference. Emission and gross income results for each enterprise were averaged across the study area and over four global circulation models before the calculation of emission intensities

Adaptation	Enterprise(s)	Relative change in CH ₄ emissions per ha			Relative change in CH ₄ emissions per \$ of livestock production		
		2030	2050	2070	2030	2050	2070
Changes due to projected future climate:	Merino ewes	-0.26	-0.36	-0.51	-0.01	-0.02	-0.01
	Crossbred ewes	-0.24	-0.30	-0.43	-0.01	-0.02	-0.01
	Wethers	-0.21	-0.29	-0.43	0.01	0.01	0.02
	Beef cows	-0.17	-0.20	-0.29	0.01	-0.01	0.00
	Steers	-0.19	-0.25	-0.37	-0.02	-0.04	-0.04
Changes due to adaptations:							
Larger body size	All enterprises	0.01	0.01	0.00	-0.01	-0.01	-0.02
Greater fleece growth	Sheep enterprises	0.01	0.01	0.01	-0.05	-0.10	-0.15
Higher conception	Breeding enterprises	0.00	0.01	0.01	-0.02	-0.03	-0.05
Larger sire body size	Crossbred ewes	0.00	-0.01	-0.02	-0.01	-0.02	-0.03
Adding lucerne to the feedbase	All enterprises	0.07	0.10	0.14	0.01	0.01	0.01
Higher soil fertility	All enterprises	0.29	0.29	0.30	0.00	0.00	0.00
Confinement feeding	All enterprises	0.14	0.16	0.17	0.00	0.00	-0.01
Zero annual legume	All enterprises	-0.02	-0.06	-0.12	0.01	0.02	0.03

Discussion

Long-term feasibility of the genetic adaptations

One of the key assumptions in this modelling analysis is that the rates of genetic gain given in Table 3 can be sustained until 2070. Several the projected phenotypes fall within the range observed in existing strains of the modelled breeds: Merino ewes can be found with a standard reference weight of 65 kg (Safari *et al.* 2007a) or a reference conception rate above 140% (Fogarty 2009), as can meat sheep with a reference conception rate of 170% and Angus cows with a mature weight of 700 kg (Costa *et al.* 2011). While a 38% increase in fleece weight seems large, half that gain was achieved by index selection over only 10 years in the QPLUS flock at Trangie (Mortimer *et al.* 2006). This 'what-if' analysis does, however, assume widespread and (for 2030) near-immediate adoption of the relevant breeding goal.

Potential usefulness of the genetic adaptations

For many of the location × enterprise combinations there is at least one genetic improvement strategy that will recover much, if not all, of the decline in operating profit. For the projected climates at 2050, adoption of the most-profitable options shown in Table 5 would recover all of the impact on profitability of 36% of livestock enterprises by value, and half or more of the impact on another 12% of livestock enterprises. For about a quarter of livestock enterprises, however, the best adaptation through livestock genetics has a relative effectiveness below 0.2 at 2050. These enterprises are concentrated in the drier regions of the study area, where the quantity of consumable forage decreases substantially under projected future climates (Moore and Ghahramani 2013); in these environments, the

increases in forage conversion efficiency required to compensate for the reduced forage availability are simply unobtainable.

For sheep, breeding for greater fleece growth was the most effective of the genetic adaptation strategies, because energy devoted to wool production returns a greater economic value than energy devoted to the growth of sheep meat. As a result, conversion efficiency of forage to income by the sheep production systems was significantly increased by breeding to redirect resources to the fleece at all locations, even for crossbred ewes (Fig. 2). The small increases in energy demand imposed by extra wool growth (0.05–0.2 MJ ME/head.day) did not significantly compromise meat production.

At the production system level, increases in biophysical efficiency from larger animal body sizes were small for all enterprises except steers (6% or less to 2070, averaging 1% at 2050). The gains in operating profit reflected in Table 4 and Fig. 1 were largely produced by lower costs, since costs of rams and bulls, shearing and animal husbandry (but not purchased stock or sale costs) were assumed to remain constant on a per-head basis. At 2050, these cost efficiencies amounted on average to an 8% reduction in cost per hectare for beef cows and crossbred ewes, 6% for wethers and 3% for Merino ewes. The greater conversion efficiency increases found for the steer enterprises presumably arose from all animals in this enterprise being young, growing stock. To the extent that husbandry and shearing costs per head increase with body size, therefore, the relative effectiveness of this genetic change will decline.

The relative effectiveness of breeding for larger body size was higher for the cattle enterprises than for the sheep enterprises (Table 4). This difference was not caused by large differentials in the benefit from higher conversion efficiency (Fig. 2) or savings

from having fewer animals to manage, but from the different geographical locations of the industries. Within the study area, cattle production is disproportionately located in the high-rainfall and eastern regions where climate change impact (the denominator of Eqn 2) is smaller, and so a smaller level of relative operating profit increase is required to return profitability to historical levels.

Breeding for increased conception rates was dominated by another genetic option for all the breeding enterprises and locations, but for the enterprises based on meat production (crossbred ewes and beef cattle) it provided a second-best approach. For the crossbred ewe enterprises, breeding for increased conception rates was unique in producing substantially greater increases at low-rainfall locations than at high-rainfall locations (Fig. 2). This response was not, however, large enough to outweigh the larger impact of climate change in lower-rainfall regions, and so the general spatial pattern of relative effectiveness remained (Fig. 1).

The results of the modelling analysis for heat tolerance should be regarded as somewhat preliminary, given the simple nature of the heat stress response functions in the GRAZPLAN ruminant model. Nevertheless, the negligible responses in Table 4 strongly suggest that livestock heat stress is a minor issue in southern Australia compared with those impacts of climate change on broadacre livestock production that arise through pasture growth, as long as shade is present (as implicit in the GRAZPLAN equations). Part of the reason for this is that the hottest locations in the study area (e.g. Dalwallinu) are also dry in summer. Not only does low relative humidity allow animals to thermoregulate more efficiently through evaporative heat loss, but animals' grazing durations during summer should be relatively short in Mediterranean environments, permitting them to shift their grazing period to the night hours (Silanikove 2000). For some southern Australian locations adjacent to the study area that have summer-dominant rainfall (e.g. the north-western plains of New South Wales), heat stress may have a significant impact.

Differences and similarities compared with feedbase-oriented adaptations

The first and most important difference between the genetic adaptations reported here and the adaptations via the feedbase analysed in a companion paper (Table 5 vs Ghahramani and Moore 2013) is that the genetic adaptations had little or no effect on aboveground net primary productivity and so resulted in only small changes in OSSR. The feedbase adaptations, on the other hand, were useful to the extent that they allowed the OSSR to increase. Because of these different modes of action – which are also reflected in the methane emissions results shown in Table 6 – it is likely that feedbase and genetic adaptations can be combined with little or no dilution of effectiveness.

The main advantage of the feedbase adaptations (especially higher soil fertility) over the genetic adaptations was that they can be employed effectively across all the livestock enterprises considered in our analysis, whereas the genetic adaptations were applicable to only a subset of enterprises (e.g. greater fleece growth) or, in the case of larger body size, had relatively low effectiveness for some enterprises. The main advantage of

the genetic adaptations over the feedbase adaptations was that the benefits from the former can be expected to increase over time; as a result, the relative effectiveness of the genetic adaptations in 2070 was comparable to, and in some cases greater than, relative effectiveness in 2030 (Table 4). The effectiveness of the feedbase adaptations, on the other hand, declined over time (table 3 of Ghahramani and Moore 2013).

The most important similarity between the feedbase and genetic adaptations lies in the spatial pattern of their effectiveness (Fig. 1; fig. 3 of Ghahramani and Moore 2013). Despite some of the adaptations giving proportionally larger effects in drier environments (Fig. 2), the greater impact of climate change on OSSR and hence profitability in drier environments means that much larger proportional improvements are needed from adaptation strategies. For a location such as Narrandera, where the amount of safely consumable herbage and hence OSSR is estimated to decline by nearly 60% at 2050, an adaptation strategy needs to more than double economic water-use efficiency to be fully effective, and none of the options examined in our analyses approaches this level.

Methane emissions from broadacre livestock systems under projected climates

From Table 6, it is clear that changes in methane emissions per hectare under projected future climates will be driven by changes in livestock numbers much more than by methane emissions per dry sheep equivalent. Even though the projected future climates result in substantial changes in the amount and pattern of pasture production (Moore and Ghahramani 2013), and also in its species composition (Ghahramani and Moore 2013), they do not alter animals' energy intake or patterns of weight change sufficiently to produce large shifts in methane emissions per kilogram of forage intake. The genetic adaptations that are the focus of this paper change the total consumption of forage very little, and are therefore also predicted to have little effect on total methane emissions over and above that induced by climate change impacts.

The feedbase-oriented adaptations to climate change analysed by Ghahramani and Moore (2013), including the introduction of substantial areas of summer-growing forages and increases in soil fertility, still leave the intra-annual pattern (rather than amount) of energy available to livestock sufficiently similar to that under historical climate that methane emissions intensity is largely unaffected (Table 6). If widely adopted, the successful feedbase adaptations are predicted to result in increases in livestock numbers that would return total methane emissions towards their historical levels without much affecting emissions intensity.

Alcock and Hegarty (2011), also using the GRAZPLAN models for a single location and historical climate, found that a range of management adaptations could improve emissions intensity by 10–20%. Many of these management changes, however, induced shifts in the average ME content of the feedbase, e.g. through changed mating dates or supplementary feeding. In keeping with our results, they found that changing to a genotype with larger body size had little effect on

emissions intensity, but for increases in conception rates they estimated a larger improvement in emissions intensity than found here for 2050 climates at our nearest location (Cootamundra).

Both experimental studies (Newton *et al.* 1994; Cantarel *et al.* 2013) and our modelling results (Ghahramani and Moore 2013) indicate that the legume content of pastures is likely to increase under climate change as long as soil phosphorus fertility is maintained. A recent laboratory study (Purcell *et al.* 2012) indicates that methane emissions per unit of ME are lower from legume forages than from grasses; if these results translate to the field and to Australian conditions, then the predictions of our analysis with respect to methane emissions intensity will require revision.

Conclusions

Our analysis suggests the most effective genetic-based adaptation options could, if fully adopted, result in recovery of most of industry profitability at 2030 and nearly all of it at 2050 as improvements in conversion efficiency and cost-effectiveness accumulate. The benefits of genetic gain will be spread unevenly across the study area, however, with producers in drier environments being forced to apply genetic improvement to fewer animals. Nonetheless, genetic improvement is a good example of a 'no-regret' adaptation to climate change that is likely to be economically beneficial under present-day climate.

The financial calculations in this analysis have used constant prices since future price and cost levels are highly uncertain. In the past, however, gains from livestock breeding have largely been used to compensate for declines in livestock producers' terms of trade. If the long-term cost-price squeeze continues and is overlaid by the climate change impacts estimated in our analysis, then the incremental adaptations we have examined may be insufficient to maintain the viability of many livestock enterprises.

As noted above, the feedbase-oriented adaptations examined by Ghahramani and Moore (2013) and the genetic adaptations examined affect the water-use efficiency of livestock systems at different points, and so are likely to be effective in tandem. The analysis of combinations of adaptations will be the subject of a final paper in this series.

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