Increasing soil fertility and altering legume-grass balance as adaptation strategies for sustainable livestock production under climate change

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Abstract
Climate change is predicted to cause reduction of the annual primary productivity in grasslands across southern Australia. Elevated atmospheric CO_2 concentrations are likely to favour legumes over grasses in temperate pastures, but legume residues have weaker structure compared to grass species. As a result, more rapidly degradable ground cover during summer can potentially increase risk of soil erosion. Managing pastures for lower legume content may prevent this issue as an adaptation option but at the cost of reduced production per animal. We applied the GRAZPLAN modelling tools to simulate potential effects of future projected climates (SRES A2 scenario) on pasture and livestock production of 24 representative livestock farms in southern Australia running five livestock enterprises. We applied historical weather data for 1970 to 1999 (as reference) and projected data from four global circulation models. Pasture and animal production were simulated for focus years at 2030, 2050 and 2070. At each location, and for each climate, we estimated the sustainable stocking rate with the current pasture composition (legume-grass mixture) and with legumes other than lucerne removed from the pastures. Increased soil fertility was also simulated as an adaptation option. At all examined locations, the legume removal option decreased the profit ($/ha) in comparison with the no adaptation option. Even applying the legume removal in association with the increased soil fertility could not make significant change from the no-adaptation case. Applying the single adaptation of increased soil fertility could partly recover decline in profitability of the farm systems, however its effectiveness decreased over time.

Keywords
Climate change adaptation, modelling, agricultural system, pasture, legume removal

Introduction
Increased anthropogenic emission of gases with greenhouse effects is expected to change global climate patterns. For southern Australia, these changes are predicted to increase temperature and decrease the annual rainfall (CSIRO 2007). Reduction in the productivity of improved pastures of Southern Australia (Cullen et al. 2009) will lead to a disproportionate decrease in the stocking rates owing to increased risk of low ground cover (Alcock et al. 2010). Thus, strategies are required to maintain permanent ground cover in order to keep sustainable stocking rate and to help soil resilience. There is evidence that increased atmospheric CO_2 concentration is likely to favour legumes over grasses in temperate pastures (e.g. Clark *et al.* 1997). However, legume residues have weaker structure compared to grass species and degrade more rapidly over summer, thus greater soil erosion risk expected unless stocking rates are reduced to compensate. Managing pastures for lower legume content might therefore allow higher stocking rates in future climates, at the cost of reduced production per animal. We applied the GRAZPLAN modelling tools to evaluate the potential effects of future projected climate (SRES A2 scenario) on pasture and livestock production of 24 representative farms across southern Australia carrying five different grazing enterprises, and to explore the effectiveness of increasing pasture fertility and removing the legume component of pastures as adaptations to the future climate.

Methods
We applied the GRAZPLAN grassland simulation models (Moore *et al.* 1997, Freer *et al*. 1997; www.csiro.au/grazplan), in order to simulate the potential effects of future projected climate on pasture and livestock production. The models simulate four effects of increased CO_2 concentration: a direct CO_2 fertilization effect, reduced transpiration due to partial stomatal closure, decreased specific leaf area, and decreased leaf nitrogen content. A range of effects of changes in soil moisture and temperature are also covered by the models. A set of 24 locations (Table 1) was selected to cover temperate southern Australia; locations were chosen to represent areas of roughly equal value of agricultural production. At each location, 5 grazing enterprises (self-replacing Merino and crossbred ewes, self-replacing Angus beef cattle, Angus steers and Merino wethers) were modelled. Within each enterprise, the same livestock genotypes, prices for livestock and wool, and variable costs of production were assumed across all locations in order to facilitate

comparisons across sites. Management policies (livestock replacement, the timing of the reproductive cycle, the sale of young stock and thresholds for supplementary feeding) were described separately for each enterprise with location combination. A "historical" scenario was simulated over the years 1970-1999 as a reference period. Climates projected by four GCMs (CCSM3, ECHAM5/MPI-OM, GFDL-CM2.1 and HadGEM1) under the SRES A2 scenario at 2030, 2050 and 2070 were downscaled into daily weather data sequences using a technique adapted from that of Zhang (2007). CO_2 concentrations of 350 ppm for historical climate and 451, 532 and 635 p.p.m at 2030, 2050 and 2070 were assumed. A factorial simulation experiment was conducted in which the factors were climate scenario (1 + 4 × 3 levels), location (25), livestock enterprise (5), pasture fertility (normal or high fertility) and pasture legume content (with or without legumes). For each combination, a range of stocking rates was modelled. Physical and financial outputs from the grazing system were stored from each simulation run. A long-term rate of operating profit was calculated as the gross margin less overhead costs, an operator allowance and a further adjustment for the capital cost of the livestock required 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); all results are reported at this stocking rate. For simplicity, only the long-term average operating profit from the most profitable enterprise under each location and climate scenario (the "maximum profit", in $/ha) is reported here. In order to compare adaptation strategies across locations with very different financial profiles, a relative "adaptation effectiveness" A_{ef} was calculated as $A_{ef} = (A_P – N_A)/(H_P – N_A)$ where A_P denotes profit after an adaptation, N_A is profit without any adaptation, and H_P is profit during the historical period.

Results

Average annual rainfalls differed widely among GCM projections. GFDL-CM2.1 showed the largest decrease of annual rainfall across the study area (11%, 12% and 25% in 2030, 2050 and 2070 respectively), while the smallest decrease was projected by the CCSM3 GCM (2%, 1% and 1% decreases in 2030, 2050 and 2070). Annual mean temperature increased at similar rates under all examined GCMs; the mean temperature increase across the study area and all GCMs was 1°C, 1.5°C and 2.4°C in 2030, 2050 and 2070. Modelled annual above-ground net primary productivity (ANPP) was highly variable among the GCM projections, with differences mainly determined by projected rainfall. For CCSM3, simulated ANPP showed an average decrease over sites of 10%, 8% and 11% in 2030, 2050 and 2070 respectively, while for GFDL-CM2.1, ANPP was estimated to decrease by 24% in 2030, 25% in 2050 and 43% in 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 55%). Launceston (Tasmania) was exceptional: an increase in ANPP was predicted there under the HADGEM1 and CCSM3.0 projections.

In the absence of adaptations, maximum profits decreased steadily from historical climate to 2070 for nearly all locations and dates. Exceptions at 2030 were Launceston (+18%), Lucindale (+20%), Mansfield (+4%), Tatura (+2%) and Stawell (+20%) under the HADGEM1 projection. At 2050, maximum profit increased at Launceston under all GCM projections and at Lucindale under only the HADGEM1 projection. At 2070, an increase in maximum profit at Lucindale was estimated under all projections except GFDL-CM2.1. The sharpest overall profit decline of adaptations was estimated to be under the HADGEM1 projection with decrease from 6%, 29% and 55% from 2030 to 2050 and 2070 respectively (Figure 1). The highest overall decrease in operating profit was under the GFDL-CM2.1 projection with 42%, 47% and 74% decline by 2030, 2050 and 2070, respectively (Figure 1). The standard deviation of annual profits decreased from historical levels to 2030, increased slightly from 2030 to 2050 and then decreased again at 2070, i.e. in general uncertainty is projected to decrease. Comparing the average value of all four GCM projections, maximum profit declined most from the reference period in South Australia, with 70%, 86% and 110% decreases in 2030, 2050 and 2070 to reference period. The smallest state-wide profit decrease was in New South Wales (36%, 45% and 51% in 2030, 2050 and 2070 respectively). Victoria had the same decline as NSW for 2030 and 2050 but was more affected in 2070 with 66% decline. In Tasmania one location was modelled which showed 6% decline at 2030, 3% increase at 2050 and 0.3% increase at 2070. Western Australia had 42%, 66% and 87% profit decline at 2030, 2050 and 2070, respectively.

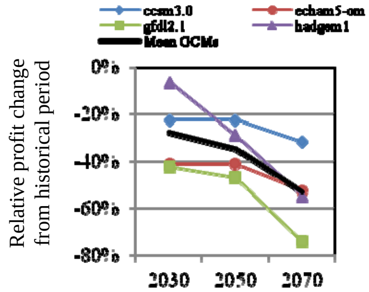


Figure 1. Decline of the profit from historical period by climate change impact for farm system with highest profitability under four GCMs.

Significant increases in maximum profit were estimated under the higher fertility adaptation strategy relative to no-adaptation at most of the 24 locations. The zero legume adaptation was estimated to have no positive effect under any GCM or future date. This suggests that even under future climates, the higher nutritive value of legumes outweighs the disadvantage of more rapid ground cover loss. The strategy of removing annual legumes plus increasing fertility generally had less effect than only higher fertility (Table 1); in a few cases, this strategy had higher operating profit for enterprises other than those shown in Table 1. Less effect of adaptation was observed in enterprises that had lower ANPP during the reference period in Western Australia and South Australia (e.g. Dalwallinu, Kyancutta, and Lake Grace). Model results showed negative profit at Lake Grace and Kyancutta even after these two adaptation strategies were implemented.

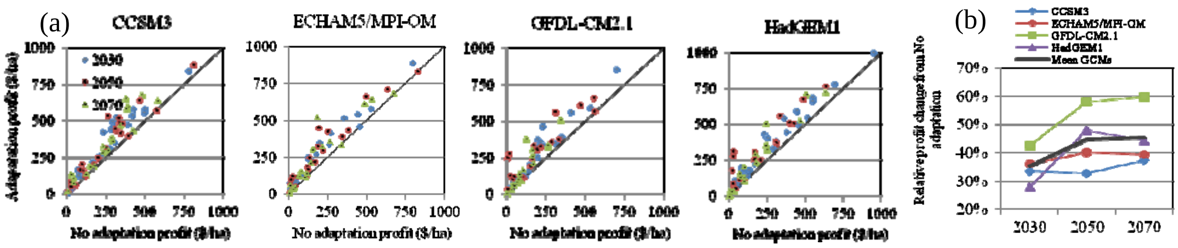
Table 1. Operating profit ($/ha) of crossbred ewe enterprise (as an example among enterprises) at each of 24 locations across southern Australia at 2050 and of three adaptations: reduced pasture legume content, increased pasture fertility, and their combination. Values are averages over four GCMs; absolute values vary widely between GCMs. "Adaptation effectiveness" is the proportion of the decrease in operating profit at each location that is recovered by means of the most effective adaptation (increased soil fertility). 0.0 = no benefit; 1.0 = a return to the 1970-99 baseline value of production, and >1 means higher income than historical period.

	Historical Climate $/ha	No Adaptation $/ha	Zero Legume $/ha	Higher Fertility $/ha	Both adaptations $/ha	Adaptation Effectiveness
Western Australia						
Dalwallinu	76	6	-2	16	3	0.15
Bakers Hill	300	160	124	429	194	0.31
Lake Grace	8	-14	-16	-10	-13	0.15
Katanning	220	164	129	209	172	0.81
Esperance	178	47	32	63	53	0.12
Mount Barker	557	342	327	n/a	344	-0.07
South Australia						
Kyancutta	8	-14	-16	-10	-13	0.15
Cummins	121	17	8	95	22	0.75
Lucindale	367	287	138	420	217	1.66
Lameroo	62	3	-10	40	4	0.63
Victoria						
Birchip	158	16	0	107	63	0.64
Colac	745	599	508	651	558	0.36
Stawell	378	240	154	341	248	0.74
Swan Hill	53	-7	-10	11	2	0.30
Tatura	303	154	122	211	173	0.38
Mansfield	345	257	213	528	321	3.05
Hamilton	1007	828	735	895	800	0.37
New South Wales						
Armidale	300	160	124	351	194	1.36
Condobolin	138	59	83	87	79	0.36
Cootamundra	449	214	196	306	284	0.39
Goulburn	277	189	161	344	275	1.77
Narrandera	243	47	31	86	64	0.20
Wellington	196	77	71	100	95	0.19
Tasmania						
Launceston	463	454	393	606	483	16.89

When averaged over all GCMs, at 2030, increased fertility adaptations had the highest effect on increasing profit in Tasmania, followed by New South Wales, Victoria, Western Australia and South Australia. In 2050, the highest effect of adaptation estimated again for Tasmania, followed by Victoria, South Australia, New

South Wales, and Western Australia. In 2070, the highest effect of adaptation among States was same as 2030. Simulated profit under increased fertility adaptation was less than historical profit but, it was, however, significantly higher in compare with no adaptation cases under all GCMs (Figure 2). Total adaptation profit of examined locations increased with comparison to no adaptation from 2030 to 2070 under CCSM3.0 and GFDL-CM2.1 but decreased for the other dates and GCM projections (Figure 2.b). Maximum profit among enterprises, increased for the mean effect of all GCMs, between 2030 and 2050, but with no effect at 2070.

Figure 2. (a) Comparison of adaptation effect on profit ($/ha) for four GCM projection of 24 locations across Southern Australia. (b) relative variation of profit ($/ha) from no daptaion



Conclusion

The GRAZPLAN modelling tools have been applied to simulate potential effects of future projected climate (four GCM projections) on pasture and livestock production of 24 representative farms across southern Australia. Modelling results estimated significant decrease in ANPP and profit of farm systems. The adaptation strategy of increasing soil fertility was estimated to have a considerable effect in recovering the decline in profit while keeping the ground cover above threshold (cover > 0.70). Only in a few of the grazing systems did legume removal plus increased soil fertility show a higher profit than increased fertility alone. It should noted that the other benefits of maintaining the sustainable ecological system (i.e. sustainable pasture cover to control soil erosion, environment quality, water quality, soil degradation, etc) have not been included in the operating profit measure used here. However, it will be necessary to apply different and complex incremental or even transformational adaptation strategies in order to sustain profit of livestock systems across southern Australia under climate change.

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