Garnaut Climate Change Review

Simulation of climate change impacts on livestock carrying capacity and production

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Executive summary

Grazing for livestock production is the major land use in Australia in terms of area. The components of livestock production examined in this report were wool and meat from both cattle and sheep. Grazing enterprises cover a wide range of climates and vegetation zones, and hence represent a complex challenge in terms of calculating the impact of climate change. The major objective of the project was to develop a simple model that allowed the impact of changes in temperature and rainfall on livestock production to be calculated by the Garnaut Review's economic modelling team. Building on a previous approach (Crimp et al. 2002), we have used the existing spatial distribution of plant growth attributes and livestock management (stocking rate, sown pastures) to develop relationships to explain the effect of spatial climate variation on livestock carrying capacity and $ value of production.

Model development

In deriving a final model for simulating national carrying capacity, eleven models were initially developed and compared. The eleven models were based on combinations of simulated pasture variables from the soil-water balance and pasture growth model GRASP (Rickert et al. 2000, McKeon et al. 2000), alternative treatments of the arid zone and either inclusion or exclusion of a livestock production index.

To parameterise the GRASP model for each climate location, pasture growth attributes were drawn from the AussieGRASS national modelling framework (Carter et al. 2000). On this basis, GRASP was used to calculate pasture growth and an index of the length of the growing season. In turn, these variables were converted to livestock carrying capacity (beef number equivalents per hectare) and $ production per hectare using relationships derived from Statistical Division data. The Statistical Divisions that constitute the arid zone of Australia (72% of area, 28% of livestock numbers) were treated in two ways, either as 22 climate locations, or as 76 climate locations. We reasoned that splitting the arid zone and including a greater number of locations in the simulation produced a more robust model for simulating national carrying capacity from climate inputs.

Eleven different models were compared using sensitivity tests with various climate change scenarios. The selected model supplied to the Garnaut Review's economic modelling team was regarded as a conservative representation of the effects of climate change in the arid and semi-arid zones, whilst providing reasonable explanation of existing spatial variation in livestock carrying capacity (LCC) in higher rainfall zones in southern Australia. The selected model included the likely effects of temperature increase on the value of livestock production.

Limitations to the approach

The limitations to the approach include: uncertainties with regard to the effects of CO_2 on pasture growth and animal diet quality; the representation of seasonal distribution of rainfall in climate change scenarios; and representation of any future adaptations which are likely to have a strong socio-economic component as well as a climatic component.

Main findings

The main findings of the project were:

- Simulated variables 'pasture growth' and 'length of the growing season' accounted for a high (>70%) proportion of spatial variability in livestock carrying capacity (cattle and sheep expressed as beef equivalents).
- The explanation of spatial variation was improved by accounting for additional factors such as tree density (expressed as tree basal area).
- The simulated variable 'length of the growing season' better accounted for variation in livestock carrying capacity in the more climatically favourable regions of south-eastern Australia.

- Livestock production (expressed as a $ value) per beef equivalent was related to the climate variable ‘temperature of the wettest quarter’ and was consistent with other studies on the effects of temperature on diet quality and other factors affecting livestock production.

- Simulation of climate change impacts on livestock carrying capacity indicated some amplification of the climate change in rainfall per se, in most regions of Australia (i.e. other than ACT, Victoria and Tasmania).

Conclusion

In conclusion, a simple model capable of simulating the impact of climate change on livestock carrying capacity and production across Australia was developed and supplied the model equations to the Garnaut Review’s economic modelling team. As part of model development the uncertainties associated with the application of the model and those areas where further research is required were also identified.

1 The development of models to simulate livestock carrying capacity and production across Australia

This report describes the procedure undertaken to simulate the impact of climate change on Australian livestock carrying capacity (LCC) and production. The main section of this report briefly describes the chronological development of 11 different models, so as to allow a sensitivity test on the approaches to calculate the impact of climate change. Appendix 1 provides a more detailed discussion of the issues raised in model review and development.

1.1 Brief description of livestock industries

In terms of area, grazing with domestic livestock is the major land use in Australia occurring across a wide diversity of climate, vegetation and topographical zones including the arid zone, dry monsoonal, semi-arid, sub humid, wet tropics, 'Mediterranean', 'temperate', and 'high rainfall' zones (Figures 1,2,3 and 4). These zones vary spatially in rainfall amount and seasonal distribution, and include summer and winter dominant rainfall regimes with very different pasture production and livestock enterprises. Wool and meat from cattle and sheep, are the predominant forms of production from the livestock enterprises considered here. In 2006, there were 25.6M beef cattle and 91M sheep, including lambs, across Australia. Dairy production, which can include irrigation as an input, is not considered in this analysis. In dollar terms (based on 2006 values), the gross value of production from cattle, sheep, and wool (CSW) was $12 billion, representing 32% of the gross value of agricultural production.

Figure 1 Spatial distribution of the gross $ value of production from cattle, sheep and wool per ha

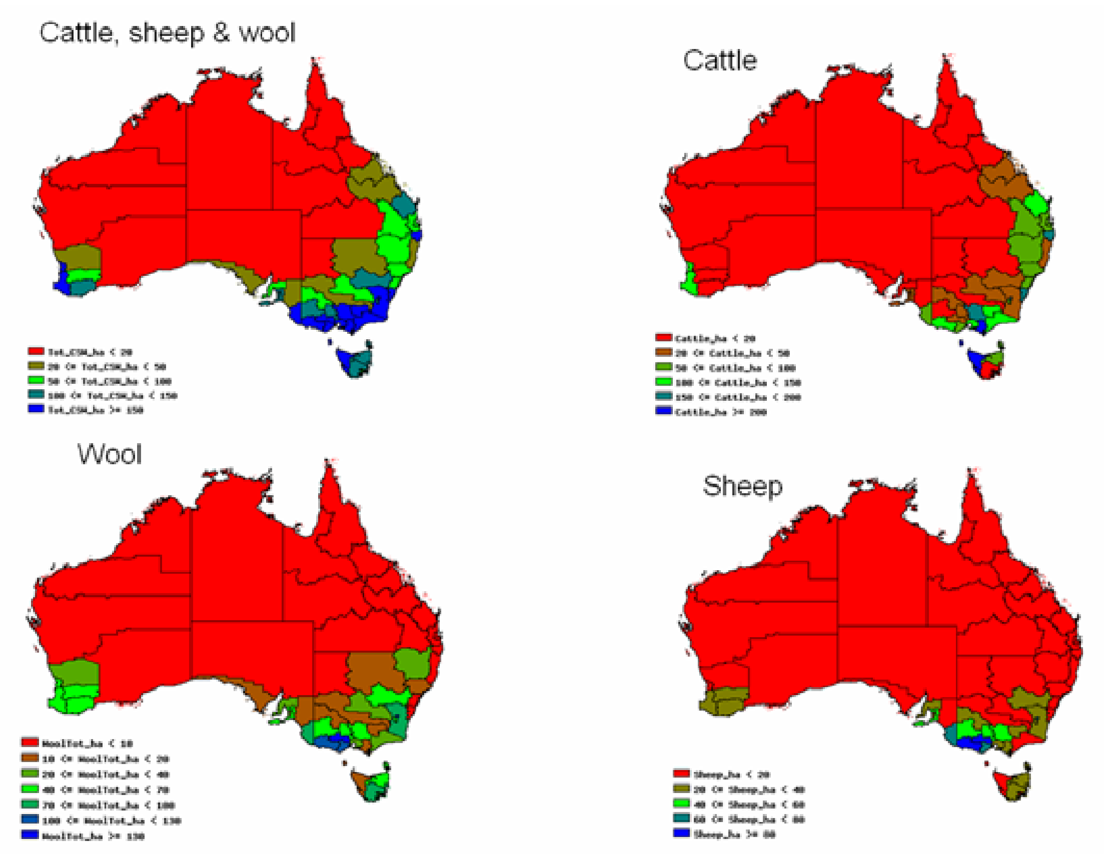


Figure 2 Distribution of sheep (from AussieGRASS, Carter et al. 2000). Numbers shown are sheep expressed as 50kg dry sheep equivalents per thousand hectares derived from 2001 ABS data

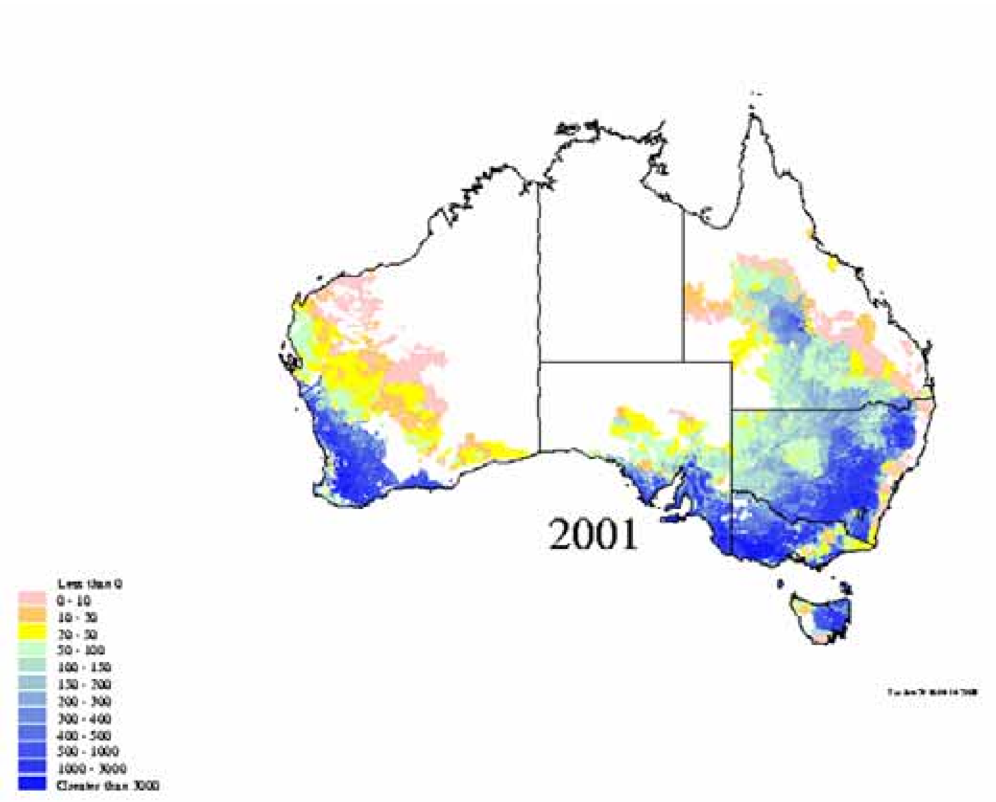


Figure 3 Distribution of cattle (from AussieGRASS, Carter et al. 2000). Numbers shown are beef cattle expressed as 400kg beef equivalents per thousand hectares derived from 2001 ABS data

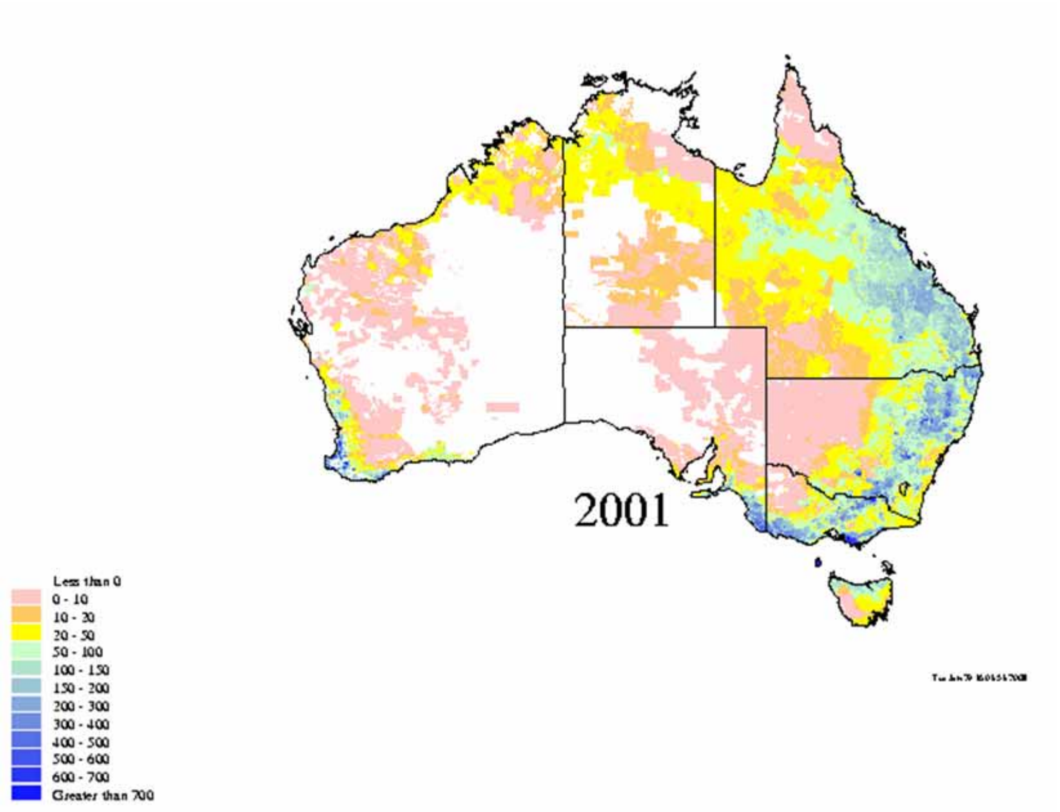
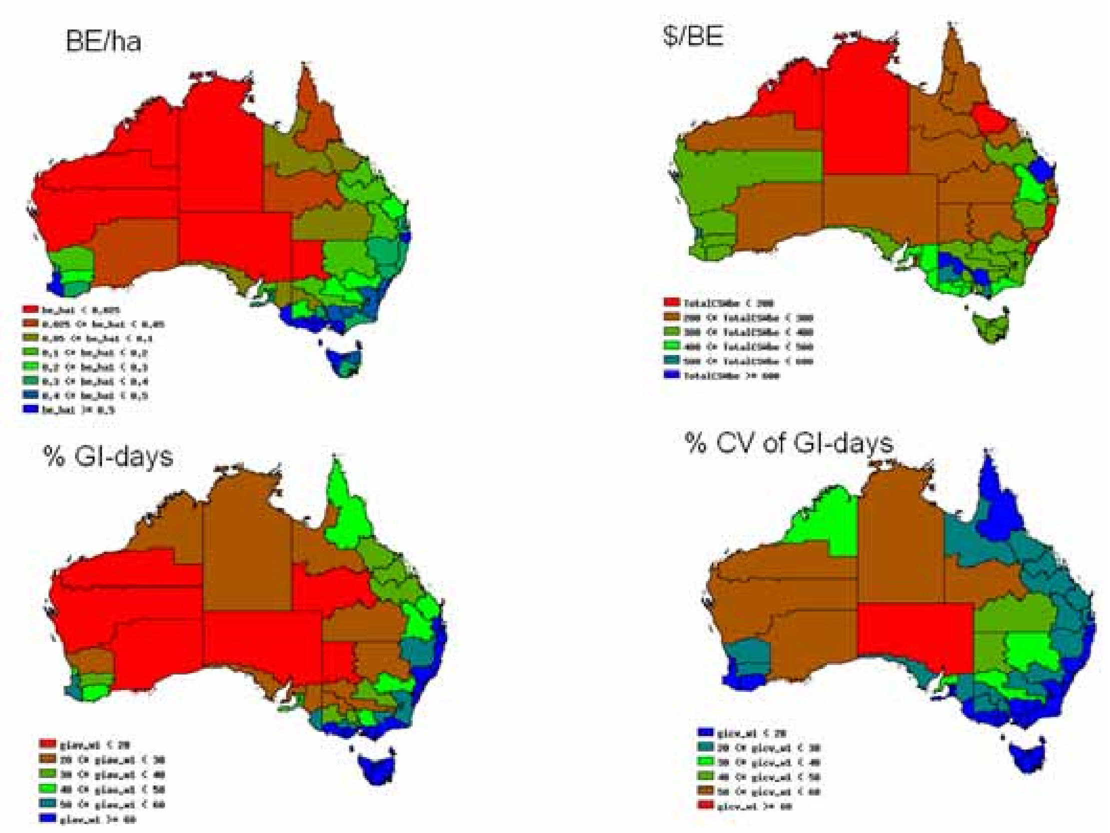


Figure 4 Distribution of components of livestock production and climate attributes: beef equivalents per ha (BE/ha); $ produced per beef equivalent ($/BE), % days the pasture growth index exceeds the threshold 0.3 (%GI-days), and coefficient of variation of %GI-days (% CV of GI-days)



The majority of production is attained from grazing pastures. There is a variable year-to-year production from feedlots, depending on grain availability and prices. Management options used by grazing enterprises to maintain and increase production vary with climate and soils. Options vary from simple property development in rangelands (watering points, paddock sub-division), to intensive inputs in climatic zones more endowed for pasture growth (historical tree clearing, woody regrowth management, fertiliser, sown pasture species, diet supplementation and irrigation). These management inputs and options represent an adaptation response to climatic constraints and opportunities. Livestock industries have a long history of development and technological uptake (including the use of well adapted breeds of sheep and cattle). Hence, for most of Australia, the current state of enterprise development is likely to reflect the near optimal management strategies for existing and historical climatic and economic constraints and opportunities. One current exception to this generalisation is the pastoral zone of the northern Northern Territory where increased LCC, as a result of property development, is anticipated to continue (N. MacDonald pers. comm.).

The arid zone of Australia is particularly important in calculating the impact of climate change because of its large area (72% of the nation) and the sensitivity of livestock carrying capacity in this region to small changes in rainfall (Wilson and Harrington, 1984). Currently the zone carries 28% of Australian livestock (sheep and cattle) expressed as beef equivalents and generates 20% of the dollars from sheep, cattle and wool. The average stocking rate in the arid zone, expressed as beef equivalents per hectare, is very low (0.03 BE/ha) compared to more climatically favourable zones. In model development, we address the arid zone using different approaches.

In this study, we have not addressed the role of feedlots or irrigation in livestock production. The use of feedlots to finish cattle is dependent on a number of factors, including price and availability of grain, prices of beef obtained in internal and export markets, and the availability of animals and feedlot capacity. A more detailed analysis of the impact of feedlots and irrigation on production from individual Statistical Divisions will be required to separate these effects from the climatic 'drivers' considered here.

The challenges in calculating the impact of climate change on livestock production are to: (a) comprehensively cover the whole of Australia including the wide range of climate and vegetation zones that support grazing enterprises; and (b) account for likely adaptation responses in terms of changes in vegetation attributes, and implementation of livestock production options (e.g. changes in stocking rates).

A third methodological challenge was to develop an approach that could rapidly calculate the impacts of a wide range of possible climate changes across a diverse range of environments and livestock enterprises and be easily implemented into complex economic models. In the following section, we describe the procedure in detail, including the issues raised by a mid-term project review. In Appendix 1, we describe in greater detail some of the strengths, limitations and uncertainties of the approach.

1.2 Review of previous approach

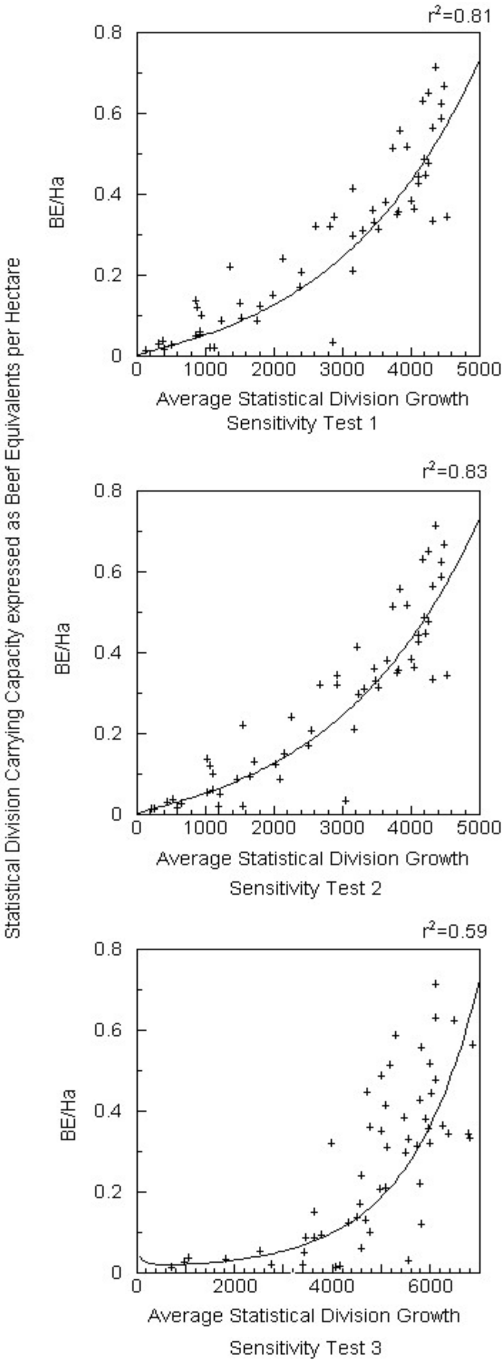
Crimp et al. (2002) developed relationships calculating LCC from native pasture growth (Figure 5) using Australian Bureau of Statistics (ABS) data from 1997. LCC was calculated by expressing cattle and sheep numbers as beef equivalents, accounting for the different pasture consumption rates between types of animals. However, an issue identified in their study was that simulated native pasture growth (with average soil fertility) did not explain the variability in LCC in the more climatically-endowed zones of Australia (south west WA, south-eastern Australia). As indicated above, in these zones, managerial options that increase pasture growth and livestock production (historical tree clearing, woody regrowth management, fertiliser, sown pastures, use of forage crops, irrigation) are practised, and have increased LCC well above that carried by native pastures. However, data allowing parameterisation of these inputs (e.g. increased soil fertility, fertiliser inputs on pasture) are yet to be processed, and hence, we developed the alternative approaches described below.

A second issue was the treatment of the arid zone of Australia. In the arid zone, LCC is very sensitive to changes in rainfall and pasture growth (Wilson and Harrington 1984, Johnston et al. 1996, McKeon et al. 1998). The representation of this zone by a relatively small number of climate locations was thought to increase the uncertainty of overall State and Australian calculations to climate change impacts. Unlike other areas of Australia, the limitations on pasture growth due to arid zone resource capability (e.g. soil fertility, topography, spatial variation in land-types) are not well described. This issue was addressed, to some extent, in model development.

The third limitation identified in reviewing the previous approach (Crimp et al. 2002) was that the current study required a calculation of the impact of climate change on relative changes in $ gross value of production from livestock rather than just LCC. We reviewed additional approaches to achieve this goal.

The approach developed by Crimp et al. (2000) provided a powerful basis for how vegetation attributes (represented as pasture growth parameters in the model GRASP) are likely to change in response to changes in climate variables (rainfall amount and distribution, temperature, humidity, solar radiation, pan evaporation). In addition, this systematic approach, using a well organised computing environment allowed rapid development of the different modelling approaches described below.

Figure 5 Average annual simulated pasture growth compared against average livestock (total beef and sheep) carrying capacity expressed as beef equivalents (BE/ha) (1994 to 2000) at the statistical division scale (Figure 8 from Crimp et al. 2002). Three sensitivity tests were conducted: Test 1, potential nitrogen uptake of 11.4 kg N/ha and dynamic grass basal area; Test 2, potential nitrogen uptake of 11.4 kg N/ha and constant grass basal area; and Test 3, potential nitrogen uptake of 20 kg N/ha and constant grass basal area. Potential nitrogen uptake of 11.4 kg N/ha is regarded as low fertility, whilst 20 kg N/ha represents average fertility.



1.3 Initial project objectives, approach and methods

The approach adopted here was to use the ‘116 point pasture growth model’ (Crimp et al. 2002) developed previously in QCCCE (then CINRS, QNRW). The 116 point model involved simulating pasture growth and other indices for two climate locations in each of the 58 Statistical Divisions across Australia (including eight capital cities). Locations of climate stations were selected on the basis of highest and lowest rainfall within the Statistical Division. Using the AussieGRASS parameter set, Crimp et al. (2002) developed a relationship between key pasture growth parameters (e.g. plant growth response to temperature) and climate variables (temperature of wettest quarter of the year). However, AussieGRASS was developed for on native pastures with low and average soil/pasture fertility. AussieGRASS parameterisation of more fertile/improved pastures in southern Australia has been more difficult and remains an uncompleted task, given the high spatial variability in pasture species, history of pasture establishment and fertiliser use in south-eastern Australia.

The specifications initially called for the simulation of a factorial of responses, namely:

Rainfall	X	Temperature	X	CO_2
-30 to + 20%		0 to 4°C		350 to 750 ppm

We revised the procedure developed in 2002 for generating parameters and streamlined the representation of climate change. We completed the first run of this procedure on 15 January 2008 for pasture growth with average pasture fertility parameters.

Subsequently we expanded the factorial to develop equations that would cover a greater range of climate change scenarios, namely:

Rainfall	X	Temperature	X	CO_2
-70 to + 40%		0 to 7°C		350 to 970 ppm

The objective was to summarise the response surfaces (livestock carrying capacity and production) derived from the factorial in the form of multiple-regression equations that could be used in economic models. The equations were provided on 3 March 2008. The procedure for representing climate changes in the daily climate files used by GRASP is described in Appendix 1. An example of the equations is given in Appendix 2.

1.4 Development of an inverse modelling approach to livestock carrying capacity

Based on consultation with economic modellers, we evaluated our assumptions in terms of the likely application of the equations and response surfaces. We concluded that a better model of livestock carrying capacity (than indicated in Figure 5) and an index of the gross $ value of production (Figure 6a) were required to simulate the Statistical Divisions with more favourable climates and higher than average pasture fertility (i.e. in southern Australia). As discussed later, a model of the $ value of production was developed from a Statistical Division data (Figure 6b).

To achieve this objective, we used an inverse modelling approach to simulate exactly the livestock carrying capacity of each Statistical Division, and hence each State and Territory.

The procedure for the initial inverse modelling approach was as follows:

- Several simulated model output variables were evaluated (Figures 5 and 7) including: average annual pasture growth; pasture growth index (0–1); and % days in the year that the growth index was above the threshold 0.3 (%GI-days). The latter variable, %GI-days, was thought to best discriminate livestock carrying capacity between Statistical Divisions with more favourable climates (Figure 8a,b). The use of the variable ‘pasture growth’, was regarded as likely to increase the uncertainties associated with soil/pasture fertility and possible interactions with the effects of increased CO_2 on plant growth.

Figure 6a The relationship between the gross value of production and livestock carrying capacity expressed as beef equivalents per ha (be/ha)

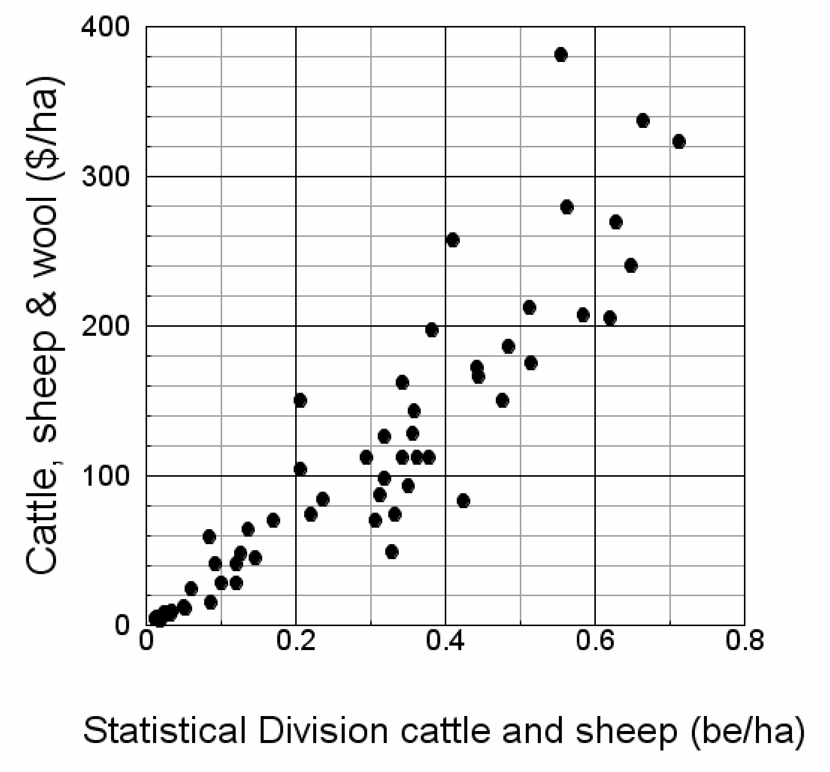
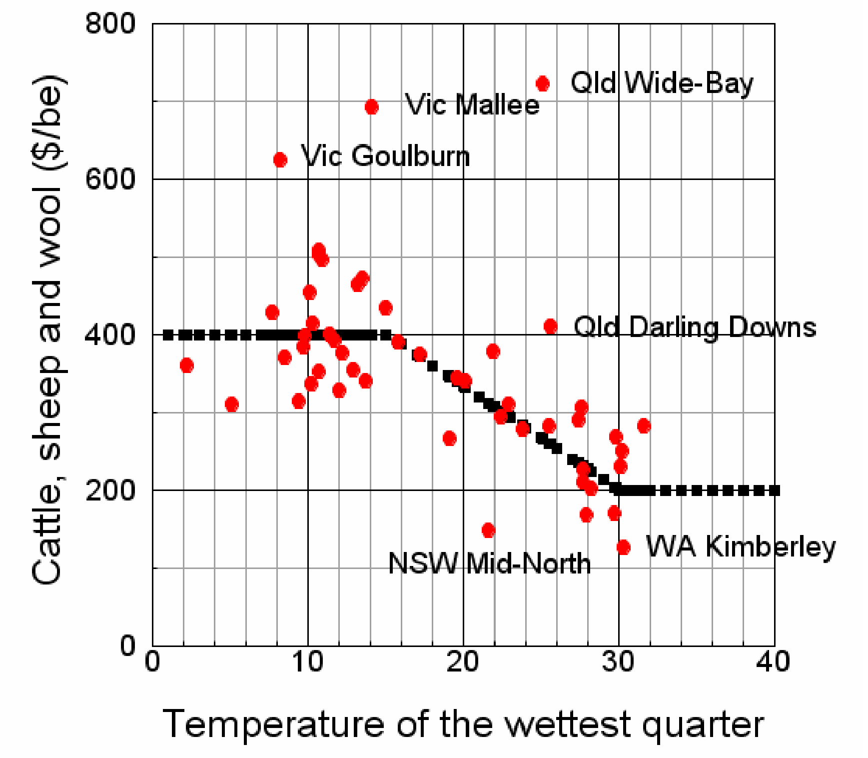


Figure 6b The relationship between the $ gross value of production per beef equivalent and temperature of the wettest quarter for each Statistical Division. The black dotted line indicates the relationship used in the simulation studies of climate change to convert LCC to $ value of production



- A general relationship was developed based on selected Statistical Divisions (Figure 8a,b). The Statistical Divisions not included were capital cities and those with high tree density (expressed as tree basal area) and/or likely irrigation inputs. The general form of the model is described as a ‘broken stick’ model (Figure 9) with a linear increasing livestock carrying capacity up to the point of the Statistical Division with the lowest carrying capacity (northern South Australia, code 435). At this point the relationship then becomes the general linear relationship derived from the 34 selected Statistical Divisions (Figure 8b). The ‘broken stick’ form of model suggests an important discontinuity in the relationship between climate (%GI-days) and LCC.

  LCC = -0.249 + 0.01337 x where x is %GI-days ($n = 34$, $r^2 = .894$)

- The general relationship (Figures 8b and 9) had been developed using spatially weighted values of %GI-days. The weightings had been previously developed by S. Crimp et al. (2002) and were based on matching the spatial rainfall of each Statistical Division to the highest and lowest rainfall climate location in each Statistical Division.

- To calculate exactly the livestock carrying capacity of each Statistical Division using the general model (Figure 8b), new weightings were derived for the two climate stations used in each Statistical Division. It was hypothesised that the new weightings better reflected the likely distribution of livestock enterprises within the Statistical Division. In 16 cases (including four in the arid zone), weighting the drier station 100% did not account for reported livestock carrying capacity, indicating that the general ‘broken stick’ model was over-estimating livestock carrying capacity. In coastal regions, this result could reflect limitations due to land use (competing land uses of forests, crops and dairy), whilst for inland regions, it was likely to reflect other limitations on LCC as described below.

- A scaling factor for each Statistical Division was derived so that the calculated livestock numbers for each Statistical Division matched the actual reported numbers. These scaling factors (ranging from 0 to 1) represent a derived limitation on pasture production and livestock carrying capacity. They are likely to reflect the combined effects on topography, soil attributes (e.g. fertility, texture and depth), woody vegetation, grazing pressure from other herbivores (macropods, rabbits, feral animals and other livestock) and year-to-year climate variability. In one case (Central Highlands Victoria) the scaling factor was substantially greater than 1.0 (1.31). This value could represent additional inputs in the production system.

- After consultation with economic modellers, we decided to add a further index to livestock carrying capacity to reflect the differences in $ value of productivity (per head) between northern and southern Australia (based on 2001 ABS data). As discussed in greater detail in Appendix 1, we attributed these differences to climate, namely temperature of the wettest quarter (Figure 6b). The implication of the production index was that as temperature increases, and southern regions of Australia become more sub-tropical or tropical, then animal productivity (expressed as $/beef equivalent) declines.

An evaluation of the initial simulation results of the above procedure indicated high sensitivity of livestock carrying capacity to climate changes in the arid zone of Australia, particularly for the regions covered by the 11 arid zone Statistical Divisions. To further test the sensitivity, an additional procedure was developed in which the 11 arid zone Statistical Divisions were treated separately, involving the simulation of 80 rather than just 22 climate stations.

Figure 7 For 50 Statistical Divisions, the relationships between livestock carrying capacity (beef equivalents per ha) and (a) rainfall; (b) annual pasture transpiration; (c) average annual growth index; and (d) coefficient of variation of a simulated stocking rate responding to climate variability.

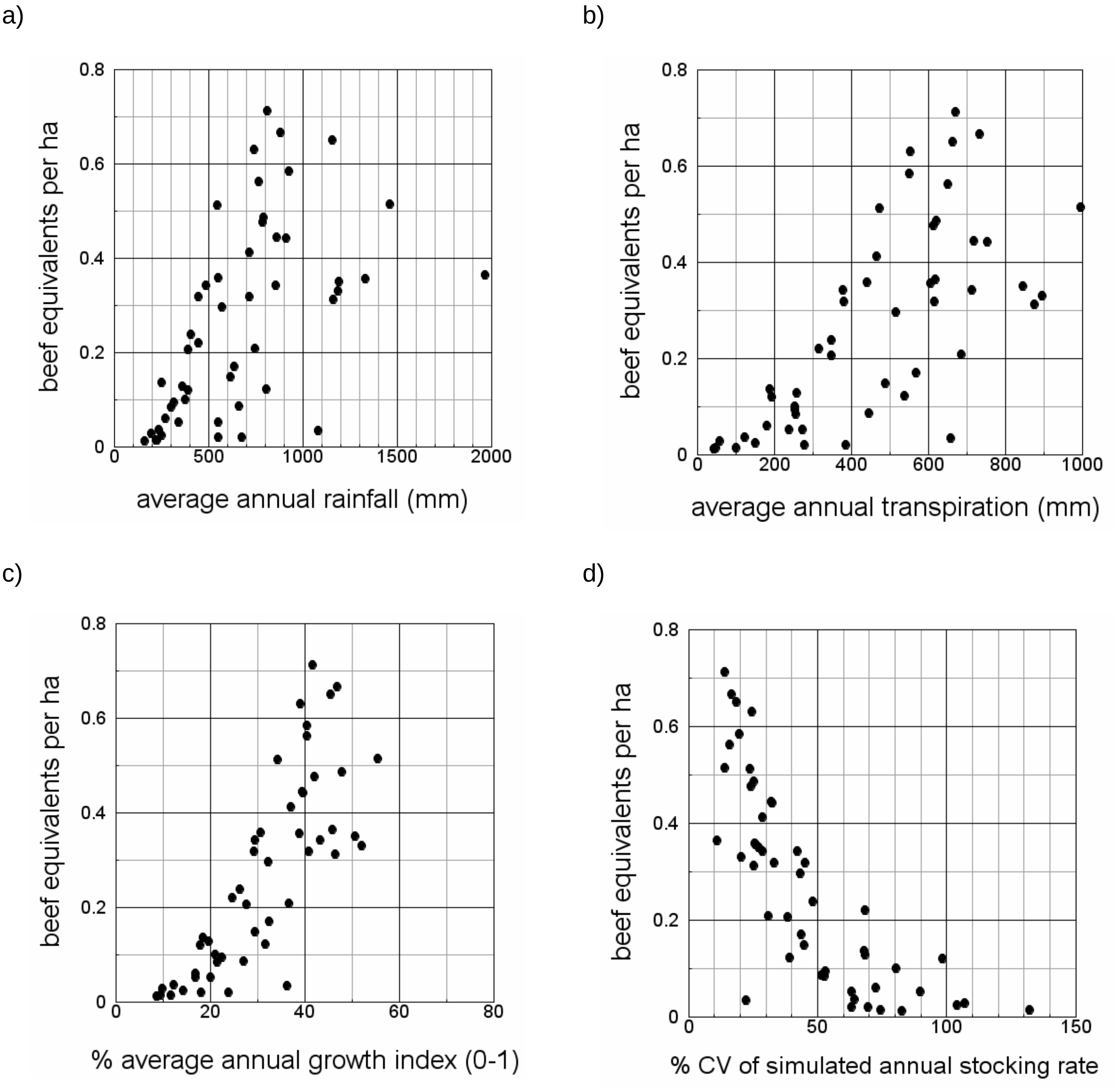


Figure 8 (a) Relationship between % growth index days (% GI-days) and beef equivalents per hectare for 50 Statistical Divisions; and (b) the linear model based on 34 selected Statistical Divisions between % growth index days and beef equivalent per hectare used in formation of the 'broken stick' model (BS1).

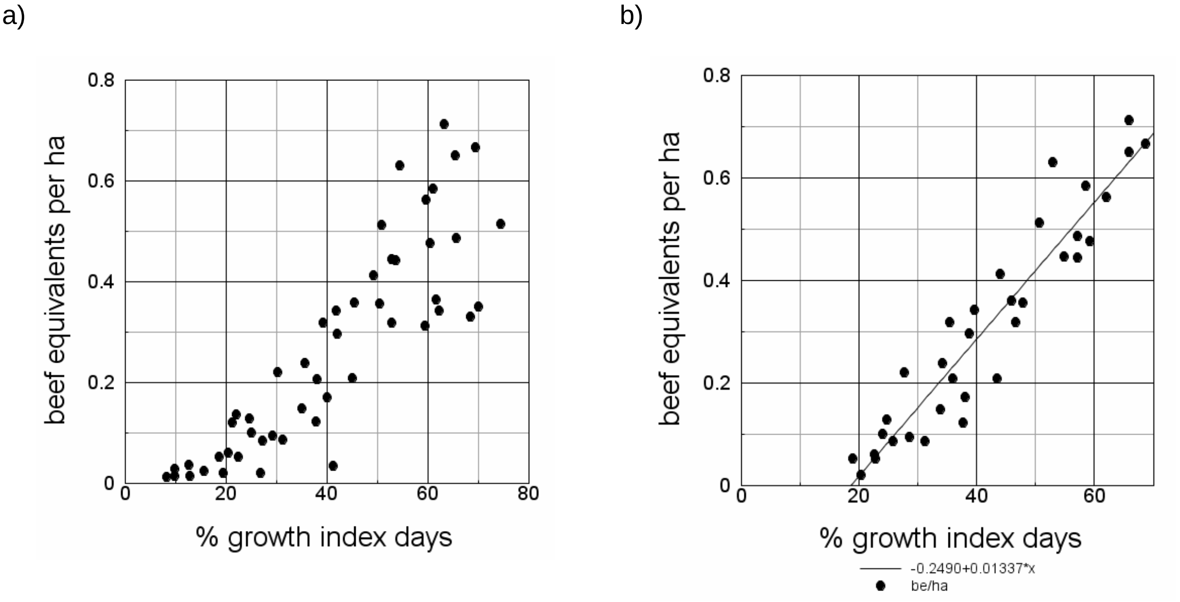
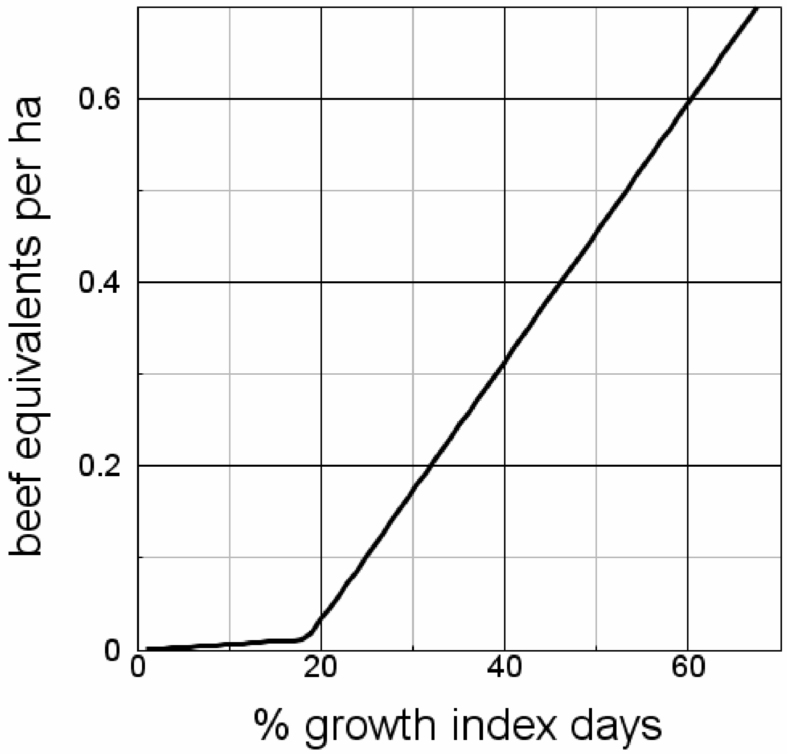


Figure 9. Schematic representation of the broken stick model of livestock carrying capacity expressed as beef equivalents (BE/ha) used in the first development of models based on % growth index days.



To address the range of issues discussed above, seven modelling options were developed for initial project review:

1. Pasture growth using average fertility parameters;
2. Pasture growth converted to beef equivalents using a curvilinear regression (after Crimp et al. 2002);
3. Growth converted to beef equivalents and then to a $ production value index;
4. %GI-days converted to beef equivalents using the ‘broken stick’ model (BS1, Figures 8 and 9;
5. %GI-days converted to beef equivalents using a combination of the ‘broken stick’ (BS1) model and the $ production value index;
6. %GI-days converted to beef equivalents using the ‘broken stick’ model and the arid zone Statistical Divisions treated separately (i.e. Split Arid Zone) with the simulation of an additional 76 climate stations; and
7. %GI-days converted to beef equivalents using the ‘broken stick’ (BS1) model and the arid zone treated separately (i.e. Split Arid Zone) with the simulation of an additional 76 climate stations and the $ production value index.

1.5 Mid-term project review

The procedure to develop these options was presented at a detailed project review (1 February 2008). Reviewers included representatives of Meat and Livestock Australia, Queensland Department of Primary Industries and Fisheries, Queensland Treasury, CSIRO Sustainable Ecosystems and the QCCCE Modelling Team. A PowerPoint presentation with more than 80 slides that describes the procedures and systems analysis in detail is available on request from the senior author.

The mid-term project review suggested the following actions:

- a more rigorous selection of Statistical Divisions to develop the general equation (between LCC and %GI-days) was required
- the effect of using the simulated variable ‘%GI-days’ rather than the variable ‘pasture growth’ needed to be further evaluated
- the application of the general model to the arid zone Statistical Divisions needed to be re-evaluated, particularly the major outlier of Far Western NSW
- testing of a curvilinear model rather than a ‘broken stick’ model was suggested to provide a smoother transition in terms of the change in livestock carrying capacity relative to change in %GI-days, particularly at the breakpoint of the ‘broken stick’ (Figure 8)
- the potential influence of trees on LCC needed to be assessed
- consequences of over-fitting in the inverse modelling procedure needed to be considered
- the implications of the large production ‘shocks’ on the economic model needed to be considered and to what extent these shocks represented true climatic limits on livestock carrying capacity and productivity
- a $ productivity index that explained the difference between northern and southern Australia was needed.

Given the time constraints of the project, not all of these issues could be researched in depth. Nevertheless, the mid-term review highlighted important issues that will eventually lead to a more robust model of livestock carrying capacity across the nation.

In response to the above project review the following model revision and development occurred:

- The more rigorous procedure in selecting Statistical Divisions to develop general models considered average tree basal area as an important source of variation in LCC. Average tree basal area was extracted from AussieGRASS data layers (Carter et al. 2000).
- The eight Statistical Divisions based on capital cities were removed. For the 50 remaining Statistical Divisions, %GI-days accounted for 74% of the variation in LCC. In a simple multiple regression, %GI-days and average tree basal area accounted for 77%, with the latter term statistically significant ($P = 0.05$). Pasture growth and average tree basal area accounted for less variation (73%).
- To develop the two new general models, 10 Statistical Divisions with tree basal area greater than 16m^2/ha were removed, improving the proportion of variation explained by %GI-days (78%) but not by pasture growth (73%). A further two 'outlier' Statistical Divisions were removed (Far North Queensland, southern Tasmania) considering lower tree basal area criteria. The remaining 38 Statistical Divisions formed the basis for the curvilinear model:

  $$\text{LCC} = 1.223 \times 10^{-4} x^{2.05} \text{ where } x \text{ is – \%GI-days } (n = 38, r^2 = 0.834)$$

  The further removal of five arid zone Statistical Divisions with low %GI-days (leaving 33) was the basis for the new broken stick model (BS2) with a new general linear model:

  $$\text{LCC} = -0.2132 + 0.0112\, x \text{ where } x \text{ is \%GI-days } (n = 33, r^2 = 0.797)$$

- New weightings and scaling factors were derived for each Statistical Division (see Table 1). These values were applied to both the 116 point model and the Split Arid Zone model (Table 1).
- Expert review comments were received supporting the use of the $ production–temperature index to modify livestock carrying capacity (detailed in Appendix 1).

Table 1 The scaling factors calculated for each Statistical Division in the Arid Zone

Statistical Division	Statistical Division code	Scaling factor applied to area of rural holdings	%GI-days	Beef equivalents per ha from Curvilinear Model	Actual beef equivalents per ha for Statistical Division
North-western NSW	135	0.7444	30.5	0.1339	0.0997
Far-western NSW	160	0.4702	19.2	0.0521	0.0245
South-western Qld	325	0.4638	27.9	0.1117	0.0518
Central-western Qld	335	0.4775	22.6	0.0727	0.0347
North-western Qld	355	0.5101	26.3	0.0990	0.0505
Northern SA	435	0.3327	15.7	0.0346	0.0115
South-eastern WA	530	0.4014	21.8	0.0675	0.0271
Central WA	535	0.2432	20.3	0.0584	0.0142
Pilbara WA	540	0.2301	20.2	0.0578	0.0133
Kimberley WA	545	0.1426	30.5	0.1339	0.0191
Northern Territory Balance	710	0.2075	25.7	0.0945	0.0196

Note: the scaling factor was calculated as the ratio of actual livestock carrying capacity (LCC) to LCC calculated from curvilinear models based on %GI-days

Thus, as result of the project review process, four additional models were developed:

Livestock carrying capacity was calculated with: a) new ‘broken stick’ (BS2) with a ‘Split Arid Zone’ (Model 8); and b) curvilinear model (Model 10) with ‘Split Arid Zone’ (Figure 10). The $ production model was applied to each of these new LCC models (resulting in Models 9 and 11), providing a total of 11 models for evaluation (Table 2 and Table 3).

Figure 10 Comparison of the various models developed to predict livestock carrying capacity expressed as beef equivalents per hectare. Broken Stick Model 1 (black line); Broken Stick Model 2 (blue line); and Curvilinear Model (red line). The first Broken Stick Model was based on subjective selection of 34 Statistical Divisions, whilst the second Broken Stick model (BS2) was developed on 33 Statistical Divisions. The Curvilinear Model was based on 38 Statistical Divisions. The data for the 38 Statistical Divisions selected for the Curvilinear model are shown.

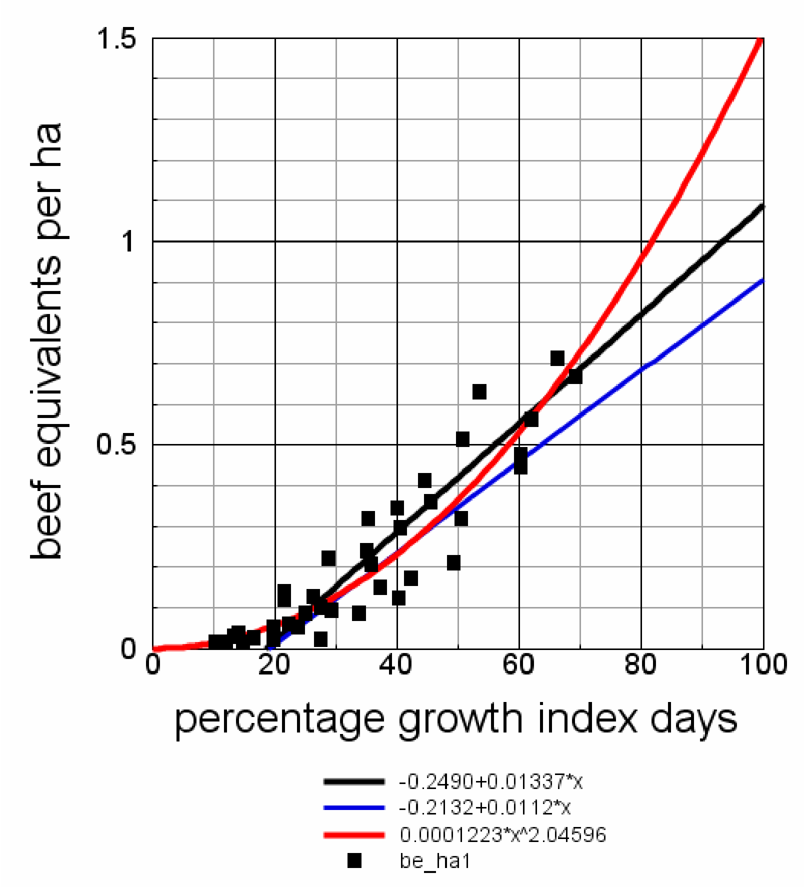


Table 2 Description of the 11 models developed to simulate the impacts of climate change on livestock carrying capacity and production from Australia's rangelands and pastures

Model	Short title	Description
1.	Growth	Pasture growth using average fertility parameters and without trees
2.	BEs from Growth	Pasture growth converted to beef equivalents using a curvilinear regression (Crimp et al. 2002)
3.	$ from BEs and Growth	Growth converted to beef equivalents and then a $ production index
4.	BEs from Broken Stick Model 1 (BS1)	%GI-days converted to beef equivalents using the 'broken stick' model (BS1, Figures 7,8)
5.	$ from Broken Stick Model 1 (BS1)	%GI-days converted to beef equivalents using a combination of the 'broken stick' (BS1) model and the $ production index
6.	BEs from BS1 and Split Arid Zone	%GI-days converted to beef equivalents using the 'broken stick' model (BS1) and the arid zone Statistical Divisions treated separately with the simulation of 76 climate stations
7.	$ from BS1 and Split Arid Zone	%GI-days converted to beef equivalents using the 'broken stick' model (BS1) and the arid zone treated separately with the simulation of 76 climate stations and a $ production index
8.	BEs from Broken Stick Model 2 BS2) and Split Arid Zone	%GI-days converted to beef equivalents using the 'broken stick 2' model (BS2, Figures 7,8)
9.	$ from Broken Stick Model 2 (BS2) and Split Arid Zone	%GI-days converted to beef equivalents using a combination of the 'broken stick 2' (BS2) model and the $ production index
10.	BEs from Curvilinear Model and Split Arid Zone	%GI-days converted to beef equivalents using the curvilinear model (Figure 10) and the arid zone Statistical Divisions treated separately with the simulation of 76 climate stations
11.	$ from Curvilinear Model and Split Arid Zone	%GI-days converted to beef equivalents using the curvilinear model and the arid zone treated separately with the simulation of an additional 76 climate stations and a $ production index (the model selected for use in climate change analysis)

Note: Model 11 was selected for use by the Garnaut Review economic modelling team.

1.6 Sensitivity of models to climate change impacts

Sensitivity studies were conducted on the 11 models (Table 3). Equations were developed to calculate the relative change in production attributes: pasture growth, livestock carrying capacity (LCC), gross value of production ($) for the whole of Australia. Single factors of climate change (e.g. temperature increase by 3°C, CO_2 increase to 750ppm, rainfall change + or – 10%) were calculated. Temperature affects several processes in the pasture model (including potential evapo-transpiration) with different effects on pasture growth compared to %GI-days. The results indicated (averaged across Australia) that, in the case of a temperature increase of 3°C, there was a small decrease (-7%) in pasture growth which was amplified in effects through to LCC (-11%) and $ (-15%). However, in the case of the models based on %GI-days, there was little effect of temperature on LCC (range 0 to +5%) and a small decline in $ (range -2 to -4%).

In the case of increasing CO_2 to 750ppm, there was an 11% increase in pasture growth, which increased to a 16% increase in terms of LCC and a similar change to $ (15%). The first 'broken stick' model (BS1) indicated similar effects, but the more conservative 'broken stick', curvilinear, and Split Arid Zone models (Models 6–11)showed less impact, with only a small increase in LCC and $ (range 2% to 5%). This moderate effect of CO_2 on production using these approaches is due to the limited effect of elevated CO_2 on growth index days—there is a small increase in GI days due to more conservative water use arising from reduced stomatal conductance. This conservative water use has been observed in experiments with elevated CO_2 in temperate pastures and savannas. This relatively low response to elevated CO_2 contrasts with other agricultural systems (e.g. wheat), where biomass production directly relates to grain production and consequently economic responses to CO_2 are likely to be much greater.

In terms of the impact of + or – 10% changes in rainfall, pasture growth showed smaller effects (+7 or -8%), but there was a greater amplification in LCC (+12 or -12%) and $ (+12 or -12%). The 'broken stick' models showed substantially higher amplification in LCC (+22 or -19%). There was slightly less impact on $ (+19 or -17%). The curvilinear Split Arid Zone model was more conservative for both LCC and $ (+13 or -12%) and hence was similar to the impact on LCC and $ calculated from pasture growth (i.e. Models 2 and 3).

For the combinations of climate changes (temperature increase of 3°C, CO_2 at 750ppm and rainfall at +20%) there was an 18% increase in pasture growth, but larger effects on both LCC (+31%) and $ (+26%). Much larger effects (+37 to +66%) depending on variable or model) were simulated by the 'broken stick' models. However, the curvilinear-Split Arid Zone models (models 10 and 11) were similar to the calculations based on LCC and $ from pasture growth (Models 2 and 3). Nevertheless, there was some amplification of the 20% increase in rainfall with respect to LCC (34% increase) and $(25% increase).

For the combinations of temperature increase of 3°C, CO_2 at 750ppm and rainfall decrease by 30%, there was a 21% decrease in pasture growth, but larger effects on LCC (-30%) and $ (-34%). Larger effects (~ -40%) were also simulated by the 'broken stick' models indicating the sensitivity of this type of model to 'drier' changes. The curvilinear-Split Arid Zone models had less decline than the broken stick models for calculations of LCC and $. There was only small amplification of the 30% decrease in rainfall with respect to LCC (32% decrease) and $ (36% decrease). We regard these changes as plausible and broadly consistent with the effects of climate change found in other studies of this type (Hall et al. 1998a,b, Howden et al. 1999a, Crimp et al. 2002).

Table 4 shows the impact of the extreme climate changes tested for each State. The extremes are a combination of high temperature changes (3–7°C) and large (positive or negative) changes in rainfall. For Tasmania and Victoria, where low temperatures are likely to limit pasture growth and the length of the growing season, relative changes in livestock production are similar to relative changes in rainfall. For the other States, the net result of the many effects of temperature, CO_2 and rainfall distribution was an amplification of changes in rainfall. However, at this stage of model development, it is difficult to separate the many effects that were represented in the pasture, LCC and $ CSW models.

Summary

From consideration of both the comments arising from the project review and the results of the sensitivity study, it was concluded that the 'Curvilinear – Split Arid Zone' model (Model 11, Tables 2 and 3) had the best features for use in large-scale studies such as economic models. This model was an improvement on the initial model (Crimp et al. 2002) based on native pasture growth with respect to both discriminating between Statistical Divisions in more favourable climatic zones and capturing likely adaptation responses in management and productivity. This model provided a more conservative and robust view of the impact that climate change could have in the more climatically sensitive and larger regions of Australia (arid and semi-arid zones). The equations derived from the factorial simulation for each State are given in Appendix 2.

Table 3 Relative change in Australia's pasture growth, livestock carrying capacity (beef equivalents, BEs) and $ of gross value produced for some example climate change scenarios

Change in temperature	% change in rainfall	CO_2	Growth	BEs from growth	$ from BEs and growth	BEs from Broken Stick Model 1 (BS1)	$ from Broken Stick Model 1 (BS1)	BEs from Broken Stick Model 1 and Split Arid Zone	$ from Broken Stick Model 1 and Split Arid Zone	BEs from Broken Stick Model 2 (BS2) and Split Arid Zone model	$ from Broken Stick Model 2 (BS2) and Split Arid Zone model	BEs from Curvilinear and Split Arid Zone model	$ from Curvilinear and Split Arid Zone model
Model Number			1	2	3	4	5	6	7	8	9	10	11
3	0	350	-7	-11	-15	5	-2	3	-3	0	-4	1	-4
0	0	750	11	16	15	14	12	5	5	5	5	2	2
0	10	350	7	12	12	22	19	19	17	18	16	13	13
0	-10	350	-8	-12	-12	-19	-17	-17	-16	-17	-15	-13	-12
3	10	750	11	18	13	41	28	30	21	27	19	19	12
3	-10	750	-4	-6	-11	-4	-10	-8	-12	-9	-13	-8	-13
3	20	750	18	31	26	66	50	52	40	47	37	34	25
3	-30	350	-29	-42	-45	-49	-48	-45	-46	-45	-45	-36	-38
0	-10	750	3	3	2	-7	-7	-13	-12	-12	-11	-11	-11
3	-10	350	-14	-22	-25	-15	-19	-15	-18	-16	-19	-12	-16
3	-10	750	-4	-6	-11	-4	-10	-8	-12	-9	-13	-8	-13
0	-30	350	-24	-34	-35	-52	-48	-47	-44	-45	-42	-36	-35
3	-30	350	-29	-42	-45	-49	-48	-45	-46	-45	-45	-36	-38
0	-30	750	-16	-22	-24	-42	-39	-43	-41	-42	-39	-35	-34
3	-30	750	-21	-30	-34	-40	-41	-40	-41	-39	-40	-32	-36
0	20	350	13	25	25	45	40	39	36	37	34	27	26
3	20	750	18	31	26	66	50	52	40	47	37	34	25

Note: The calculations were made using the equations derived for Australia as a whole (i.e. not individual States). The shading indicates the main treatments discussed in the text.

Table 4 Sensitivity tests of climate change scenarios (wet and dry) for individual States using equations derived from Model 11 (Curvilinear-Split Arid Zone Dollars model)

State in temperature scenario	Change in temperature °C	% change in rainfall	% change in livestock production	Amplification (A) or reduction (R)
ACT	4.7	10.9	15.96	A
ACT	5.6	-44.4	-40.42	R
NSW	5.1	22.8	27.78	A
NSW	6.3	-54.6	-62.13	A
NT_	5.6	32.4	37.28	A
NT_	6.8	-61.6	-69.46	A
QLD	5.3	32.5	50.47	A
QLD	6.5	-61.8	-70.62	A
SA_	5.0	21.9	30.06	A
SA_	6.2	-70.8	-82.82	A
TAS	3.2	14.0	13.92	=
TAS	4.0	-28.3	-30.03	=
VIC	4.2	5.1	7.03	=
VIC	5.2	-44.7	-43.17	=
WA_	5.6	22.8	29.32	A
WA_	6.8	-68.5	-76.75	A

1.7 Conclusion and future research

The study reported here addressed the very complex issue of simulating livestock carrying capacity and production from a wide range of climates, soils, topography, vegetation, and livestock enterprises. Nevertheless, a derived index of pasture and livestock performance (%GI-days) was found to account for a high proportion of spatial variability in livestock carrying capacity at a Statistical Division level and hence, formed the basis for evaluating climate change impacts. The application of a general model indicated that more research is required on:

- the choice of representative climate stations for livestock enterprises in each Statistical Division, particularly in the arid, semi-arid and northern Australian regions
- documentation of additional inputs to pasture and livestock production, especially in climatically favourable zones (sown pastures, fertiliser, crop residues, irrigation, dietary supplementation, feeding hay and/or grain)
- modelling combined dairy and livestock (sheep and cattle) production as a function of climate and other inputs (irrigation availability)
- the factors (e.g. soil fertility, temporal variability in rainfall, property development) that limit pasture and livestock production in the arid, semi-arid and northern Australian regions
- potential change in land use including the future role of trees and forestry as competing or value-adding land uses
- the climatic component of limitations to livestock production in sub-tropical and tropical environments
- the long-term (10–30 years) effect of increased CO_2 on pasture and livestock production

- the representation of within-year (i.e. seasonal) distribution of rainfall changes and potential increases in climate variability with climate change.

In this study, we included two main responses to climate change:

1. likely change in pasture growth parameters, particularly temperature response; and
2. likely change in managerial inputs such as stocking rate and pasture-production inputs.

In each case, we have assumed that the existing response of pastures and livestock enterprises, that are described in the model parameters and relationships, represent near-optimal adaptation to existing and historical climatic and economic conditions. The model parameters and relationships have been derived from the existing spatial distribution of climatic variability and then used to simulate the impact of new climatic regimes. Thus, in general terms, we have used existing spatial variation in climatic impacts to address the issue of representing vegetation and managerial adaptation. However, major limitations to this approach are:

- managerial adaptation will be dependent on socio-economic factors such as costs of inputs (fertiliser, supplements) and delivery to markets, prices received for commodities, and regulations regarding land use, downstream effects such as water quality, and greenhouse gas emissions. All of these are likely to change in the future
- the allocation of land resources to livestock enterprises will be dependent on the 'success' of competing land uses (e.g. cropping, dairy, forestry, conservation) which, in turn, are influenced by climate, particularly with regard to rainfall
- the change in livestock enterprises to the new vegetation and managerial regimes, implicitly modelled in the use of the spatial relationships derived in this study, may not necessarily proceed in a straightforward path. The temporal processes of vegetation and managerial adaptation are yet to be modelled and will have to consider the processes of enterprise change, adoption, extension and government support, investment availability for property development, and management for year-to-year and decadal variability in rainfall.

A further major issue not addressed in this study was the risk of resource degradation associated with climate change. A review of historical degradation and recovery episodes in Australia's grazing lands (McKeon et al. 2004) highlighted the potential for the mis-match between stock numbers and pasture growth on short-term (2–5 years) timescales to cause resource degradation. From a livestock production perspective, climate changes involving increases in rainfall may lead to increased density of woody vegetation unless stock numbers and pasture burning are managed (Burrows et al. 2002). The climate changes that include a decline in rainfall will require careful adaptation strategies involving reduction in stock numbers so that the resource and future potential productivity are not damaged. The models developed here provide some guidance as to what adaptation responses will be required but the pathway of change is yet to be researched.

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Appendix 1 Review of model development, issues and future actions

The following section describes in more detail some of the issues raised in developing the procedure. Given the time constraints for model development and the complexity of the task, not all issues could be resolved and hence, expert judgement was required to proceed. The basis for these decisions is discussed below, including some of the consequences and future actions required to improve the model.

A1.1 Features of GRASP and AussieGRASS used by Crimp et al. (2002)

The model developed by Crimp et al. (2002) had several features suitable for a comprehensive analysis of calculating the impact of climate change on LCC. A key component of the approach was the use of a general pasture model across the nation.

- The approach was based on the soil water–pasture growth model GRASP (Rickert et al. 2000, McKeon et al. 2000) which had been developed, parameterised and validated with field data for a wide range of pastures across Australia's rangelands and native pastures. GRASP had also been formally compared to other models covering a wide range of pasture types (arid zone, Hobbs et al. 1994, and sown pastures, Moore et al. 1997) and was able to be parameterised for these situations (Richards et al. 2001, Tupper et al. 2001).

- In AussieGRASS, the model GRASP had been parameterised for over 180 pasture communities using remote sensing and field data. AussieGRASS (Carter et al. 2000) simulates pasture growth at a 5km grid scale across Australia and is used operationally for a number of applications including the relative assessment of drought conditions in 'near' real-time.

- In previous studies, calculated pasture growth has explained a high proportion of variation in LCC at a property and regional scale (Scanlan et al. 1994, Johnston et al. 1996, Day et al. 1997, Hall et al. 1998a,b, Johnston et al. 2000). Simulations with historical climate data correctly identified previous periods of resource and economic stress at the scale of both grazing enterprises (Landsberg et al. 1998) and of large regions such as Statistical Divisions (McKeon et al. 2004).

- A key feature of climatic effects on pasture growth in Australia are the limitations of moisture and temperature (Fitzpatrick and Nix 1970). GRASP calculates a daily pasture growth index combining the effects of moisture, temperature and solar radiation. Temperature can limit growth in winter even though moisture and solar radiation are adequate for growth. Thus, increases in temperature can increase potential plant growth in many locations.

- The simulated variable 'percentage of days the pasture growth index exceeded a threshold value' (%GI-days) explained a high proportion of livestock production in rangeland and native pasture grazing experiments (after McCown 1980, Hall 1996, McKeon et al. 2000).

- GRASP has been parameterised to include some of the effects of increasing CO_2 (Howden et al. 1998, 1999a,b) as discussed below in more detail.

Thus, GRASP provides a sound basis for a national simulation of pasture growth and livestock production indices.

A1.2 Adaptation of vegetation response to climate change

A challenge in simulating the impact of climate change is to calculate the likely change in pasture species composition and the response to limiting factors such as temperature. Native pasture systems include a wide range of species, however, particular situations are often dominated by a few species (Tothill and Gillies 1992). Hence the effect of climate change on pasture growth may be dominated by the large but as yet unpredictable response of individual species. Changes in pasture composition to species better adapted to a new climate are likely to occur through natural (e.g. competition and/or invasion) and managerial (e.g. new species sown) processes. Crimp et al. (2002) developed an initial approach to represent the change in vegetation response by using the existing spatial distribution of pasture community attributes as parameterised in AussieGRASS.

Because of the importance of temperature effects on pasture growth (Fitzpatrick and Nix 1970), and the variation in response to temperature between plant species and pasture communities, we describe the approach used by Crimp et al. (2002) in more detail here.

The pasture growth parameters have been plausibly linked to the climate attributes for each pasture community (Crimp et al. 2002). For example, key parameters describing the effect of temperature on plant growth are: (1) temperature required for growth to commence (T1); (2) temperature for optimal growth (T2); (3) supra-optimal temperature at which growth begins to decline (T3); and (4) supra-optimal temperature when growth stops (T4). These temperature parameters have been derived from laboratory (growth cabinet) research (e.g. Fitzpatrick and Nix 1970, Ivory and Whiteman 1978) and, for pasture communities, from time series of green cover measured in field work or with remote sensing (NDVI, Carter et al. 2000, 2003). The variation between pasture communities in temperature response parameters reflects the higher temperature requirements for growth of some species such as tropical or C_4 grasses. Crimp et al. (2000) found that the temperature response parameters of pasture communities were related to logical climate attributes such as temperature of the wettest quarter, (i.e. the main period of moisture availability). The relationship suggests that locations were likely to be dominated by pasture species best adapted to the main season of growth. Thus, these relationships provide a plausible basis for estimating the ‘adaptive’ changes that are likely to occur in pasture communities in response to temperature and rainfall changes. In the study reported here, we reviewed these relationships and made small changes to allow extrapolation to a greater range of climate (mainly temperature) changes.

A1.3 Linking temperature and $ value of production per animal

A specification in developing equations representing the impact of climate change was to ‘translate’ changes in rainfall and temperature into relative changes in gross $ value of livestock production (from cattle, sheep and wool, $ CSW). The previous study (Crimp et al. 2002) calculated the impact of climate change on LCC. In general terms, across the 50 Statistical Divisions (i.e. excluding capital cities), $ CSW per ha was correlated with LCC (beef equivalents per ha, Figure 6a). However, investigation of the variable ‘$ production per beef equivalent’ ($ CSW per BE) suggested that values were higher in the more temperate regions of southern Australia (Figure 6b).

There are a number of contributing reasons (McKeon et al. 1993) that $ CSW per BE is likely to be higher in southern Australia than in northern Australia:

- There are a greater proportion of sheep and wool enterprises in southern Australia (Figures 2 and 3). Historically, sheep enterprises have been attempted in far northern Australia and coastal Queensland but have not been successful (Hall et al. 1998a,b). The causes reviewed by Hall et al. (1998a,b) include: the direct effects of high temperature on sheep reproduction and mortality in flocks; the deleterious effects of tropical grasses on contamination in wool and in causing animal mortality (e.g. black spear grass seed heads); loss of animals and production to pests (e.g. dingos) and diseases (e.g. worms); and the intensive labour requirements of wool enterprises.

- Increased temperature in tropical climates reduces forage quality by decreasing digestibility and the proportion of leaf material produced, and diluting available nutrients, especially nitrogen and phosphorus to levels that do not support animal growth (Wilson 1982).

- In northern Australia, there may be a reduced opportunity for direct input of supplements to improve animal nutrition due to costs resulting from long distances and restricted access in arid and far northern Australia. Similarly, the use of sown pastures including legumes has been limited by the high cost, low fertility and uncertainty of pasture establishment (e.g. Gramshaw et al. 1993).

- High temperatures and humidity have a direct effect on animal performance, restricting heat loss from metabolism and reducing food intake (Howden and Turnpenny, 1997, Petty et al. 1998, Howden et al. 1999c). Similarly, high temperatures/heat loads reduce grazing time and increase the need for water consumption (King 1983).

- Tropical conditions of high temperature and rainfall favour development of a range of diseases and vectors (ticks, buffalo fly, Leptospirosis, ephemeral fever) which can result in loss of production and increased mortality, depending on breed (Sutherst 1991, White et al. 2003).

Summary

To summarise these effects, an index of gross value of production ($ CSW/BE) was derived from the relationship between $ CSW/BE and temperature of the wettest quarter across 50 Statistical Divisions of Australia (Figure 6b). The major Statistical Division outliers are likely to include feedlots and irrigation. For example, the Darling Downs (Southern Queensland) beef cattle production includes the intensive input of grains. As the above discussion indicates, a more detailed investigation is required on the links between climate and $ value of production per head. After consultation with experts, we have used the above relationship (Figure 6b) in this study rather than assume no effects of climate change on the $ value of livestock production.

A1.4 Modelling the effect of increasing CO_2 on livestock carrying capacity and production

In previous studies on rangelands and native pastures, LCC has been calculated from pasture growth and potential utilisation. GRASP has been used to simulate both pasture growth (kg/ha/year). LCC is calculated from potential utilisation which is related to the length of growing season, i.e. the simulated variable %GI-days (Hall et al. 1998a, b). This approach explained a high proportion of the observed variation in utilisation rates across the climatic zones in northern Australia. These zones ranged from relatively ‘short’ growing seasons in dry monsoonal climates, to longer growing seasons where winter and spring rainfall occur (e.g. southern coastal Queensland). The lack of nutrients, particularly protein in the dry season, contributes to the low utilisation rates that occur in the dry monsoonal regions of northern Australia (Hall et al. 1998a,b). Thus, in representing the effects of CO_2 on LCC, it is important to not only consider the effect on plant growth, but also on the length of the growing season and pasture quality (e.g. protein or nitrogen concentration, digestibility). We hypothesise (as discussed in greater detail below) that whilst increased CO_2 is likely to potentially increase pasture growth and extend the growing season through more conservative water use, nutrient concentrations are likely to decline, hence reducing potential livestock utilisation rates. Thus, in the study reported here, we have adopted a model based on %GI-days providing a more conservative approach to representing the effects of CO_2 on LCC (Table 3).

The effect of carbon dioxide on pasture production and water use

Increased concentration of CO_2 is expected to have a range of impacts on vegetation and hydrology (Howden et al. 1998, 1999a). Increased CO_2 results in a reduced rate of transpiration, resulting in higher soil moisture conditions, and possibly a longer growing seasons if temperatures are suitable. There are direct effects of increased CO_2 on radiation and transpiration use efficiencies, resulting in increased dry matter production if nutrients are available. There is likely to be a decline in the nitrogen concentration of plant tissue as a result of CO_2 increase especially in C_3 species. There is some debate as to how long the effects of CO_2 fertilisation that have been measured in field experiments might continue and the interactions with future warming (e.g. Hovenden et al. 2008). There is a decline in plant CO_2 response as a result of down-regulation of photosynthesis and also an immobilisation of nitrogen, resulting in less nitrogen available for plant growth, a process termed ‘progressive N limitation’ (Luo et al., 2004).

In GRASP, the effects of increased CO_2 were represented (after Howden et al. 1998, 1999a,b, Hall et al. 1998b, Crimp et al. 2002) as follows:

- increase in radiation use efficiency
- an increase in transpiration use efficiency

- reduced daily transpiration (relative to the same green cover under current CO_2 concentrations)
- increased rate of nitrogen uptake per mm of transpiration.

As yet, there are no representations in the model of CO_2 effects on other important parameters such as the soil-water threshold for above-ground plant growth, potential nitrogen uptake, minimum nitrogen concentration at which growth stops, and CO_2 effects on temperature response. In the study reported here, trees were not included in the simulation of pasture growth, and hence the effects of CO_2 on tree-grass competition were not considered. However, in more complex simulations of native pastures that include variable tree and shrub density, the effects of CO_2 on tree-grass balance are likely to be very important. CO_2 effects on vegetation are continuing to be researched and new sub-models in GRASP are being developed which will address some of the uncertainties described above.

Changes in C_3/C_4 composition

In the study reported here, the effects of changes in temperature and rainfall on C_3/C_4 composition were estimated. Increases in CO_2 are also likely to influence changes in species composition (Howden et al. 1999b). Increase in temperature of the wettest quarter is likely to increase C_4 composition, whilst an increase in CO_2 is likely to increase C_3 composition. Soil attributes (available water range, fertility) also influence composition in the same climate zone. Given the uncertainty of the long-term nature of CO_2 effects on vegetation, we have represented only the effect of changing temperature on species (C_3/C_4) composition in the study reported here,.

Comparison of models with regard to CO_2 effects

In terms of the simulation of CO_2 effects on livestock carrying capacity, the two model types i.e. based on either plant growth or %GI-days, were expected to have different responses. For the pasture growth based model, an increase of CO_2 from 350 to 750 ppm resulted in an overall increase of pasture growth of 11% and 16% in terms of LCC (Models 1 and 2). Similarly, the ‘Broken Stick’ model (BS1) of LCC based on %GI-days had a 14% increase (Model 4). However, in the case of models that were based on %GI-days and combined with a Split Arid Zone model, there was only a small increase in LCC (+5%) (Models 6, 8, 10). Previous simulations suggested large impacts of CO_2 on pasture growth in the arid zone (Howden et al. 1998). However, the more conservative representation of the arid zone in the Split Arid Zone models reduced the impact of increasing CO_2 on overall Australian LCC and production.

It is uncertain whether substantial increases in pasture growth are likely to occur in situations where nutrient availability (particularly nitrogen) is likely to remain as a limiting factor (e.g. Robbins et al. 1989, Cobiac 2007). Furthermore, the increased production of pasture components (e.g. leaf and stem) of low nitrogen concentration is likely to lead to immobilisation of nitrogen, placing further potential limitations on pasture growth production (and livestock production). It is also likely that the lower nitrogen concentration in pastures is likely to reduce potential utilisation rates by livestock (Hall et al. 1998a and b). The extent to which these limitations are overcome by technological inputs is likely to depend on economic evaluation including prices received for livestock commodities and costs of manufacture and delivery of inputs.

We regard the parameterisation of CO_2 effects in GRASP as incomplete. Data from recent experiments on CO_2 effects on pastures are yet to be analysed in terms of developing sub-models and parameters. The representation of long-term effects (10–30 years) of CO_2 fertilisation through effects on nitrogen availability will be important for simulating native pasture response. Hence, the use of carbon-nitrogen cycle grassland models such as CENTURY (Parton et al. 1993) will be required to help parameterise the nitrogen sub-model in GRASP.

Some of the future climate change scenarios that were to be evaluated included very high values of CO_2 concentration (970 ppm). However, we were not confident of parameterisations of the GRASP model at levels above 750 ppm and hence we adopted a conservative view of limiting the response to CO_2 at 750 ppm. Plant responses to CO_2 concentration typically are asymptotic with limited response above 750ppm (e.g. Tubiello et al. 2007) and so this approach is unlikely to introduce serious errors.

A1.5 Woody vegetation: trees and shrubs

Trees and shrubs are a major component of rangelands and native pastures. For example, in Queensland, 60Mha of the 160Mha of pasture lands have a major woody component (Burrows et al. 2002). In rangeland communities, shrubs, depending on species, can be either regarded as 'woody weeds' or as an important diet component especially in drought (McKeon et al. 2004). Woody species compete with pasture (grasses) for moisture and nutrients. Where it has been perceived to be of economic benefit, woodlands have been cleared to increase pasture production and LCC (Burrows et al. 1990). Historically, grassland burning has had a major role in maintaining the woodland–grassland balance and improving animal nutrition (Winter 1987). However, with increased consumption of pasture (i.e. fuel) by grazing, woodland thickening has been a major issue reducing pasture productivity (e.g. Anon 1969, Burrows et al. 2002). The ability to clear woody vegetation is now constrained by biodiversity and carbon stock issues.

Parameterisation of the effect of CO_2 on woody plant growth is yet to be tested in GRASP. It is assumed in this study that the relationship between %GI-days and LCC will not be affected by the relative differences in woody and pasture responses. The scaling factors (Section 1.5, e.g. Table 1) derived for each Statistical Division are also likely to reflect a woody component. Where trees and pastures are spatially separated (e.g. trees on ridges and pastures in valley floors), then the Statistical Division scaling factors derived here are likely to continue in the future, assuming that land use (grazing compared to forestry) does not change. However, where trees and pasture are in direct competition (e.g. open woodlands of northern Australia), then the future balance between trees and grasslands is uncertain, being dependent on the different vegetation responses to climate, CO_2 and management.

A1.6 The representation of climate change in daily climate files

Base files of daily climate were obtained from the SILO database (Jeffery et al. 2001). The base period used was 1980 to 1999.

Climate changes were implemented as follows:

- temperature change was added equally to both daily maximum and minimum temperatures
- rainfall percentage change was applied to each day's rainfall
- to change vapour pressure, relative humidity was calculated from minimum temperature and vapour pressure in the base file and then relative humidity was applied to the new minimum temperature to calculate new vapour pressure
- solar radiation was assumed to be unchanged
- pan evaporation was calculated using the equation -0.810 + 0.188 VPD + 0.168 Solar, where VPD is vapour pressure deficit (hPa) and Solar is solar radiation (MJ/m^2)

The multiple regression equation for calculating pan evaporation was derived from observed data across the continent and is consistent with previous approaches used to estimate changes in pan evaporation (McKeon et al. 1998). However, the equation does not include the effects of wind, and hence, does not represent possible changes in this climate variable. The issue of 'downscaling' of climate change scenarios is still a subject of research. Given the time constraints of the project, the approach adopted here was based on previous experience in simple representation of climate changes (McKeon et al. 1998, Hall et al. 1998a,b). Some of the implications for models of LCC are discussed below.

In this study we considered the two simulated variables 'pasture growth' and '%GI-days' in terms of their explanation of spatial variation in livestock carrying capacities for Statistical Divisions. As identified in Crimp et al. (2002), pasture growth using average soil fertility did not discriminate between Statistical Divisions in favourable climates where sown pastures and fertiliser can be used to increase production. We found that %GI-days was able to better explain the wide range in livestock carrying capacities across the nation. In previous studies (Hall et al. 1998a, b), we also found that

%GI-days was better at explaining the difference in livestock carrying capacity between regions in northern Australia which had similar average annual pasture growth, but different livestock carrying capacity. In previous studies we also found that %GI-days provided more explanation of animal production attributes such as liveweight gain and wool production per head. Thus, we chose to represent the impacts of climate change using the variable %GI-days in calculating livestock carrying capacities. However, the variable %GI-days is likely to be more sensitive to the within-year distribution of rainfall and temperature than pasture growth. Thus, in representing climate change scenarios, it is important to consider likely effects of changes in seasonal climate variables, especially rainfall.

In the study reported here, the aim was to cover a wide range of changes in annual rainfall and temperature and, hence, it has not been possible to consider seasonal distribution of climate change as an additional factor. Furthermore, the representation of changes in rainfall in daily climate files requires a more sophisticated treatment than could be undertaken in this study (e.g. McKeon et al. 1998). We used the simplistic approach of applying a multiplier to existing daily rainfall in the base daily climate files (1980–1999). However, it is expected that future climate changes may involve changes in number of rain days and rainfall intensity. Changes in distribution of rainfall at the day/month timescales are likely to also influence or be associated with changes in other climate variables (temperature, humidity, solar radiation, potential evapo-transpiration). Hence, a more detailed approach to ‘downscaling’ climate change scenarios is required to more accurately represent climate change scenarios in terms of input into daily time-step models such as GRASP.

Appendix 2 Examples of the equations for each state

[Derived from the factorial of climate changes using the Curvilinear-Split Arid Zone $ Production Index Model (Model 11, Tables 2 and 3)]

Dependant variable is percentage change in total dollars production. Coefficients of regression between climate change parameters and the dependant variable. The fit is a multi-variate quadratic of the variables Dt, Dr and C, where: Dt = delta T, i.e. change in temperature (deg C); Dr = delta R, i.e. change in rainfall (as a percentage); and C = absolute CO2 concentration, in ppm. Output has two lines per state. First line is the coefficients (and R-squared), second line has the corresponding p-values, giving significance for each coefficient (i.e. a value of p greater than, say, 0.05 would indicate that the coefficient is not significantly different to zero).

	R-sq	Const	Dt	Dr	C	Dt*Dr	Dt*C	Dr*C	Dt^2	Dr^2	C^2	Dt*Dr*C
ACT	1	-3.338	2.884	0.9399	0.01092	-0.005128	-0.0002719	5.47E-05	-0.4672	-0.0008805	-3.97E-06	-2.81E-06
P-values	0	0	0	0	0.003	0.111	0	0	0	0.036	0.292	
NSW	1	-2.476	-1.912	1.232	0.008068	-0.02232	0.00146	3.33E-05	-0.03841	0.002286	-3.51E-06	1.51E-05
P-values	0	0	0	0.001	0	0	0.001	0.007	0	0.063	0	
NT	1	-4.49	-3.442	1.186	0.01452	-0.03322	0.002124	7.18E-05	0.008349	0.002027	-5.86E-06	2.16E-05
P-values	0	0	0	0	0	0	0	0.603	0	0.006	0	
QLD	0.99	-5.077	-4.615	1.331	0.01651	-0.02866	0.002777	8.18E-05	0.2382	0.00368	-6.95E-06	2.83E-05
P-values	0	0	0	0	0	0	0	0	0	0.006	0	
SA	1	-1.75	-1.458	1.455	0.0057	-0.02588	0.001389	2.57E-05	-0.1584	0.004445	-2.58E-06	1.46E-05
P-values	0.003	0	0	0.014	0	0	0.013	0	0	0.166	0	
TAS	1	-1.311	-0.3353	1.048	0.004177	-0.01768	0.0004308	1.96E-05	-0.201	0.0003093	-1.49E-06	4.29E-06
P-values	0.007	0	0	0.026	0	0.002	0.019	0	0	0.327	0.044	
VIC	1	0.6903	0.2062	0.9999	-0.002418	-0.006893	0.001036	-1.77E-05	-0.1272	-0.0002486	8.10E-07	1.05E-05
P-values	0.245	0.078	0	0.293	0	0	0.086	0	0	0.663	0	
WA	1	-2.697	-0.9897	1.272	0.008799	-0.0197	0.001182	4.37E-05	-0.1431	0.002695	-3.58E-06	1.216E-05
P-values	0	0	0	0	0	0	0	0	0	0.049	0	
AUSTRALIA	1	-2.474	-1.913	1.23	0.008029	-0.02094	0.001599	3.63E-05	-0.02671	0.002317	-3.45E-06	1.64E-05
P-values	0	0	0	0.001	0	0	0.001	0.068	0	0.076	0	

CSW—production from cattle, sheep (meat) and wool
LCC—livestock carrying capacity
Growth index—simulated index of plant growth (0–1)
%GI-days—% days in the year that the growth index was above the threshold 0.3
BEs/ha—Beef equivalents (sheep and cattle) per hectare
ABS—Australian Bureau of Statistics
GRASP—GRASP (short for grass production) is a soil-water balance pasture-growth model.
AussieGRASS—is the implementation of the GRASP model at a 5km grid scale across Australia.