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PRACTICAL ADAPTATION TO CLIMATE CHANGE IN REGIONAL NATURAL RESOURCE MANAGEMENT

Queensland Case Studies – Fitzroy Basin Report - Part A

Australian Greenhouse Office
Sinclair Knight Merz
Queensland Murray Darling Basin Committee
Desert Channels Queensland
Fitzroy Basin Association
South East Queensland Western Catchments

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healthy land –OUR FUTURE
AN INTEGRATED REGIONAL NATURAL RESOURCE MANAGEMENT PLAN FOR THE WESTERN CATCHMENTS OF SOUTH-EAST QUEENSLAND

Queensland Murray Darling Committee Inc.

SINCLAIR KNIGHT MERZ SKM

Australian Government
Department of the Environment and Heritage
Australian Greenhouse Office

Queensland Government
Climate Change Centre of Excellence
Department of Natural Resources and Water

PRACTICAL ADAPTATION TO CLIMATE CHANGE IN REGIONAL NATURAL RESOURCE MANAGEMENT

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Project No: EP08

Qld Case Studies – Report for Fitzroy Basin Association Case Study Part A – Production and natural resource indicators in beef systems under climate change conditions.

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Cover: Fitzroy Basin cattle and pastures. Photos courtesy of Ian Partridge, Department of Primary Industries and Fisheries (top left), Fitzroy River and Coastal Catchments, Central Highlands Regional Resource Use Planning Project and Fitzroy Basin Association.

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Executive Summary

A number of general circulation models (9) and greenhouse gas emission scenarios (3) were examined. The wettest, driest and average climate scenarios for the region were identified to provide a range of projected temperature, evaporation and rainfall change in 2030. In addition, one climate change scenario was used in a pasture model to assess changes in natural resources and beef production. This scenario used projected transient CO_2 concentrations in 2030 derived from IS92a, a climate change scenario simulating intermediate population growth, economic growth and fossil fuel supplies. Changes in climate, soils, pasture and beef production were measured against a base period from 1961-1990.

The dry scenario for 2030 was associated with a mean temperature increase of 1.4^{o}C, reduced annual rainfall of 9% and higher evaporation of 10%. The wet scenario for 2030 was associated with a mean temperature increase of 0.9^{o}C, higher annual rainfall of 2% and higher evaporation of 2%.

Annual rainfall projections range from slightly wetter, to much drier than the historical climate. Seasonally, changes are uncertain in DJF and to a lesser extent in MAM but are dominated by decreases in JJA and SON. Changes in potential evaporation are much more certain. **Rainfall change had a greater impact than temperature change for all indicators.**

The risk of climate change causing unmanageable increases in mean runoff in 2030 was low because the high rainfall scenario wasn't associated with more runoff than that currently experienced. Keeping stocking rates of livestock to sustainable levels (10-20% utilisation) will help maintain ground cover and continue to keep the risk of excessive runoff in 2030 low. High stocking rates (40% utilisation) increase the chance of high runoff causing soil erosion, loss of top soil and high sediment loads in waterways.

The low rainfall scenario was associated with lower mean runoff, reduced risk of excessive erosion events and reduced inflows into watercourses and dams. Water storages may need to be larger to capture more water from large, but less frequent, runoff events and water efficient methods applied that reduce evaporation, seepage and other wastage.

The low rainfall scenario reduced both the frequency and amount of deep drainage. This may reduce the threat of salinity but also limit water availability to deep rooted grasses, schrubs and trees. This may promote shallow rootedness and reduce drought tolerance of perennial vegetation. Maintaining a good basal grass cover may become more important to foster water infiltration at the soil surface and movement through the soil profile.

The risk of high deep drainage levels under high rainfall scenarios was not different to that in 1990.

The low rainfall scenario was associated with increased variability of annual growth. The higher variability will make it more difficult to sustainably manage stocking rate. Finding the balance between utilising pastures for animal production and leaving them understocked for recovery will become more difficult and better tools are needed to help pastoralists assess pasture quantity and quality, sustainable stocking rates and recovery times of pastures.

Low rainfall scenarios increased the risk of less than 1500 kg/ha of annual growth. This heightened risk of drought may force changes in drought policy, cause changes in enterprise mix (e.g. grain to grazing, grazing to feedlots) and animal species (more *Bos* *indicus* cattle, possibly with sheep), early destocking practices, increase size of viable properties, prolong pasture recovery phases and increase the risk of land ownership on low equity rates. More droughts may also reduce the incidence and prevalence of parasites (e.g. cattle tick) and disease.

The high rainfall scenarios were associated with lower annual variability in pasture growth. However higher rainfall can only produce more growth when nitrogen is not limiting so the application of exogenous sources (e.g. fertilizer, legumes) will need further economic investigation under these circumstances. The use of seasonal rainfall forecasting will be important and the economic implications of fertilizer application may depend on the accuracy of the forecast.

When rainfall was not limiting the high temperature scenario was sufficient to lengthen the growing season during winter and increase annual growth. When rainfall was limiting the high temperature scenario exacerbated moisture stress and lowered growth.

Climate change scenarios did not affect the mean TSDM compared to 1990 although there was increased risk of low TSDM (<1000 kg/ha) under low rainfall scenarios, and particularly under the high temperature/low rainfall scenario.

The low rainfall climate change scenario was associated with an overall reduction in basal area of about 10% by 2030. The risk of a basal area of <2.5% occurring will rise from near zero in 1990 to about 1 in every 3 years by 2030. Maintaining a good basal grass cover will become more important to foster water infiltration at the soil surface and movement of water through the soil profile. Keeping stocking rates to sustainable levels (10-20% utilisation) will help maintain ground cover (sum of basal area, pasture canopy cover and litter cover) and continue to help reduce the risk of excessive runoff and poor infiltration in 2030. The high rainfall climate change scenario was associated with an overall increase in basal area of around 5% by 2030.

When rainfall was not limiting, the high temperature scenario triggered a response in the pasture that produced significantly more LWG/hd. The high temperature scenario was sufficient to lengthen the growing season during winter, increasing annual growth and LWG/hd.

The low rainfall climate change scenarios were associated with increased risk of low annual LWG/hd and higher variability compared to 1990. Maintaining stocking rates at sustainable levels (10-20% utilisation) will maintain the efficiency of live weight gain and be a useful tactic in managing the greater variability of production expected under low rainfall climate change conditions. The high rainfall scenarios were associated with a higher overall LWG/hd. This opportunity was more attainable with a safe constant stocking rate than a responsive stocking rate based on feed availability.

Climate change did not significantly increase the animal production risk beyond the variability currently generated by stocking strategy and utilisation level. However individual land managers may need to adapt by altering the mix of stocking strategies or changing utilisation of pasture to better suit the changing climatic conditions. They will need training and tools to help assess pasture biomass and quality, forecast rainfall and pasture growth, adjust utilisation of pastures and balance production and resource priorities to ensure profitable and sustainable pastoral industries.

1. Project overview

The project involved seven regional natural resource management (NRM) organisations - including the Fitzroy Basin Association (FBA), Queensland Murray-Darling Basin Committee (QMDC) – and the Queensland Department of Natural Resources and Water. It was coordinated by Sinclair Knight Merz.

The project has two main objectives, as follows:

1. improve understanding of the implications of climate change for regional NRM
2. develop tools and processes that help regional NRM organisations incorporate climate change impacts, adaptations and vulnerability into their planning processes.

The project was divided into three main stages:

Stage A. This stage identified components of participating region's natural resource system that were more vulnerable to climate change. The key steps were to develop the 'conceptual mapping' workshop process, conduct a literature review to document climate change projections, impacts and adaptive mechanisms for each participating region and then to run 'conceptual mapping' workshops in each of these regions.

Stage B. This stage completed a series of regional case studies which explored climate change impacts on one or a small number of components of the natural resource system that were more vulnerable to climate change. The case studies were designed to provide more objective information on climate change impacts and vulnerability and will be used to support analysis of how regional NRM processes can incorporate climate change considerations. Results of the case study for FBA are reported here and will be used by each of the participating NRM regions to complete Stage C.

Stage C. The final stage, in which lessons from the case study will be used to help develop tools and processes (e.g. thinking models, numerical models, workshop processes, modifications to risk assessment processes) that enable regional NRM organisations to incorporate climate change into their planning, priority setting and implementation. A series of workshops will be held in each state to receive feedback on the tools and processes developed or identified through the project.

2. Objectives of the case study

Earlier work in this project (Stage A) completed a review of literature and assessment of the likely impacts of climate change in the Fitzroy Basin (Miles *et al*. 2005), and is available from the Fitzroy Basin Association or Queensland Murray Darling Committee in Toowoomba. A meeting was held in Rockhampton (September 2005) to help the community better understand the drivers, pressures and impacts of climate change, and to plan the responses that maybe useful to prepare for climate change (Stage A). During this process a number of key issues were identified related to climate change (Clifton and Turner 2005). This report provides a scientific assessment (Stage B) of one key issue in the region, namely; under climate change conditions for 2030 identify changes in:

1. Regional rainfall, temperature and evaporation; and
2. Production and natural resource indicators in beef systems.

3. The Fitzroy Basin

The Fitzroy Basin is one of the largest in Queensland, covering an area of approximately 142,500 km^2 (Figure 1). It includes the catchment of the Fitzroy River and its major tributaries: the Dawson, Comet, Nogoa, Mackenzie, Isaac and Connors Rivers. The Fitzroy is the largest river basin on the east coast of Australia, and drains to the southern end of the Great Barrier Reef, just south-east of Rockhampton. The catchment is one of the richest areas in the state in terms of land, mineral and water resources, and supports grazing, irrigated and dryland agriculture, mining, forestry and tourism land uses. It contains about 10% of Queensland's agricultural land and 95% of the catchment is under agricultural land-use comprised of about 87% grazing and 8% cropping.

The climate of the Fitzroy Basin is subtropical to tropical, ranging from humid near the coast to semi-arid inland. There is a wide range of diverse environments within the catchment, comprising higher rainfall areas of the Great Dividing Range near the coast with up to 1,200 mm of mean annual rainfall declining to approximately 500 mm inland. There is a pronounced wet season in the summer months which produces high seasonal flows and frequent flood events following monsoonal downpours and tropical cyclones. Flows are highly variable, with many of the rivers having very low flows, or drying altogether during the dry season.

The Fitzroy Basin system is divided into the following sub-systems: Isaac–Connors, Nogoa, Comet, Upper Dawson, Lower Dawson, Upper Mackenzie, Lower Mackenzie and the (lower) Fitzroy (see Figure 1).

There is mounting evidence supporting climate change in Australia (IPCC 1996, Torok and Nicholls 1996, McKeon *et al.* 1998, McKeon *et al.* 1993, Whetton 2001) yet the likely impacts on agricultural industries at the regional scale are uncertain. The distribution of different industries reflect climatically imposed boundaries and the relative economic capability of alternative land use. A shift in these relationships due to climatic change may create opportunities for industries not operating at optimal levels, but alternatively, industries operating at optimal levels may be threatened. This study provides an assessment of the likely impacts of plausible climate change to the beef industry in central Queensland.

Central Queensland makes a significant contribution to the states $2.7B (2000/01) pastoral industry and managing climate variability effectively is a key requirement for continued high levels of production. In addition to climatic variability, trends in Queenslands grazing lands related to climate change (McKeon *et al.* 1998, McKeon *et al.* 1993), and increases in atmospheric carbon dioxide (CO_2) raise questions about the future productivity of various industries, particularly those on the climatic margins (Howden *et al.* 1999). For example, if the expansion of cropping, at the expense of grazing, in the Emerald region from the early 1970's to the early 1990's resulted because of long-term climate variability then cropping is likely to decline when conditions return to those experienced earlier. On the other hand, as Howden *et al.* (1999) suggests, the increase in cropping was most likely related to environmental change (both climate and CO_2 changes), and as such, cropping areas in the region are likely persist.

The impact of climate change and increased CO_2 on different sectors of the beef industry in central Queensland has not been investigated. The dominant native pasture species is *Dichanthium*, which occurs in woodland and cleared landscapes. In more fertile areas these native pastures have been cleared of timber and sown to more productive grasses such as buffel grass. Here we investigate the impacts of the most likely and plausible climate change scenarios at Emerald with average fertility and no trees.

In a study of the likely impacts of climate change on Queenslands beef industry Hall *et al.* (1998) showed the negative effects of climate change on plant growth (+ 3^{o}C, -10% rainfall) to reduce safe carrying capacity in central Queensland by –6 to 12%. However a major finding was the mitigating effect of doubling CO_2 on the combined negative effect of lower rainfall and warmer temperatures on safe carrying capacity, where the negative effect was reduced from –6% to 8% at Emerald. Since then the blunt approach of doubling CO_2 levels has been replaced by using transient increases in CO_2 concentration that are a function of time and approximate current projections from observed data (IPCC 1996). This study uses projected transient CO_2 concentrations in 2030 derived from IS92a, a climate change scenario simulating intermediate population growth, economic growth and fossil fuel supplies (Leggett *et al*. 1992).

The complexity of the biophysical systems, the interactions between soil, vegetation and animals and extreme climate variability restrict our ability to determine the impact of climate change. In this study we use a pasture growth model to examine the sensitivity of different pastoral parameters to a range of climate change scenarios.

Figure 1. The Fitzroy River Basin showing major catchments

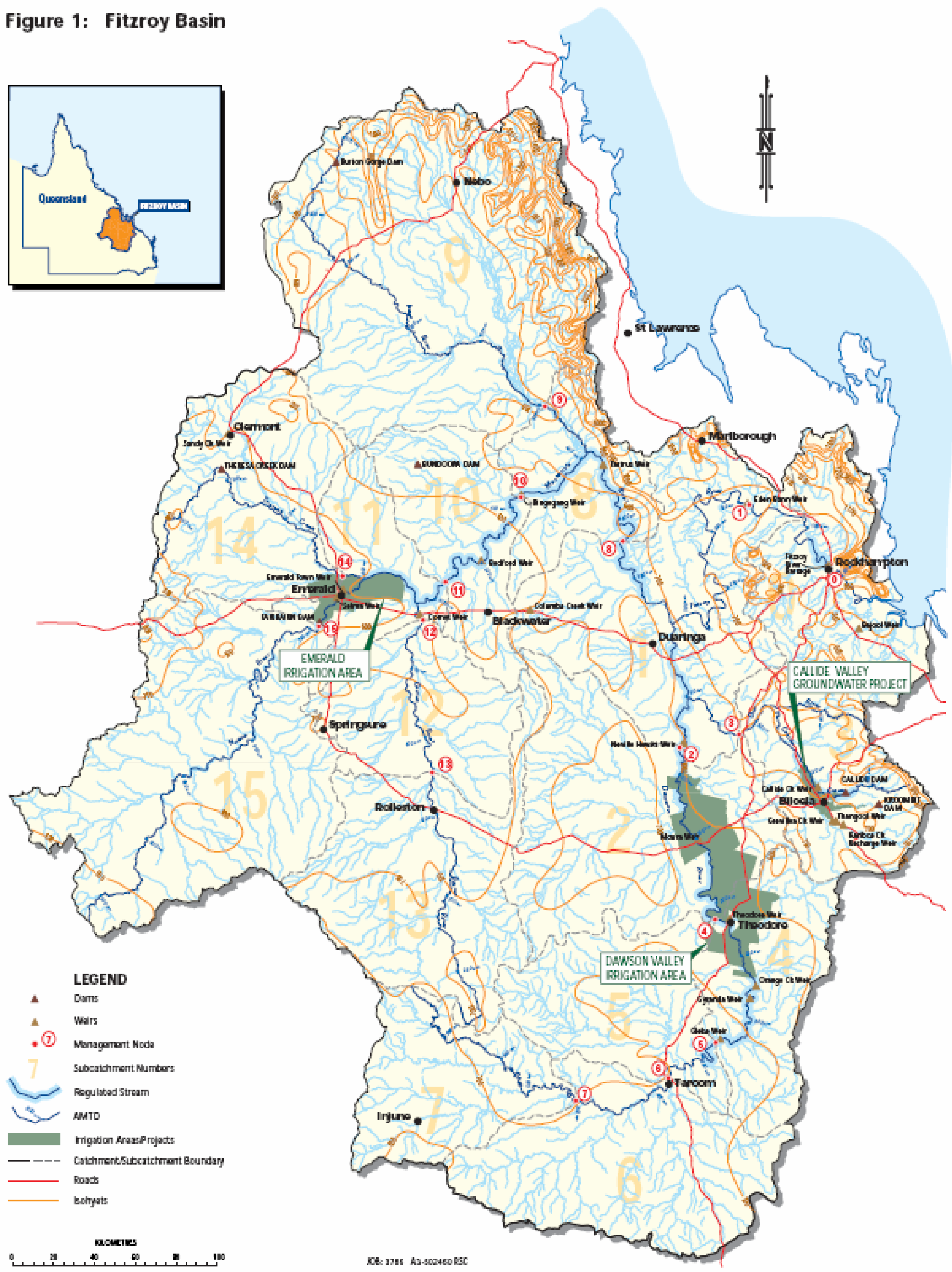

Figure 2. Stream network, location of major nodes, topography and sub-catchments of the Fitzroy River Basin.

4. The climate change scenarios

4.1. UNCERTAINITY IN CLIMATE CHANGE

Three major climate-related uncertainties were considered in this study. The first two are global uncertainties, which include the future emission rates of greenhouse gases and the sensitivity of the climate system's response to the radiative balance altered by these gases. Both uncertainties are portrayed in Figure 3, which shows the range in global warming to 2100, based on the Special Report on Emission Scenarios (SRES; Nakiçenovic *et al.* 2000) and IPCC (2001). The dark grey shading shows emission-related uncertainties, where all the SRES scenarios have been applied to models at constant 2.5°C climate sensitivity. The light grey envelope shows the uncertainty due to climate sensitivity ranging from 1.5–4.5°C (measured as the warming seen in an atmospheric climate model when pre-industrial CO_2 is doubled). These uncertainties contribute about equally to the range of warming in 2100.

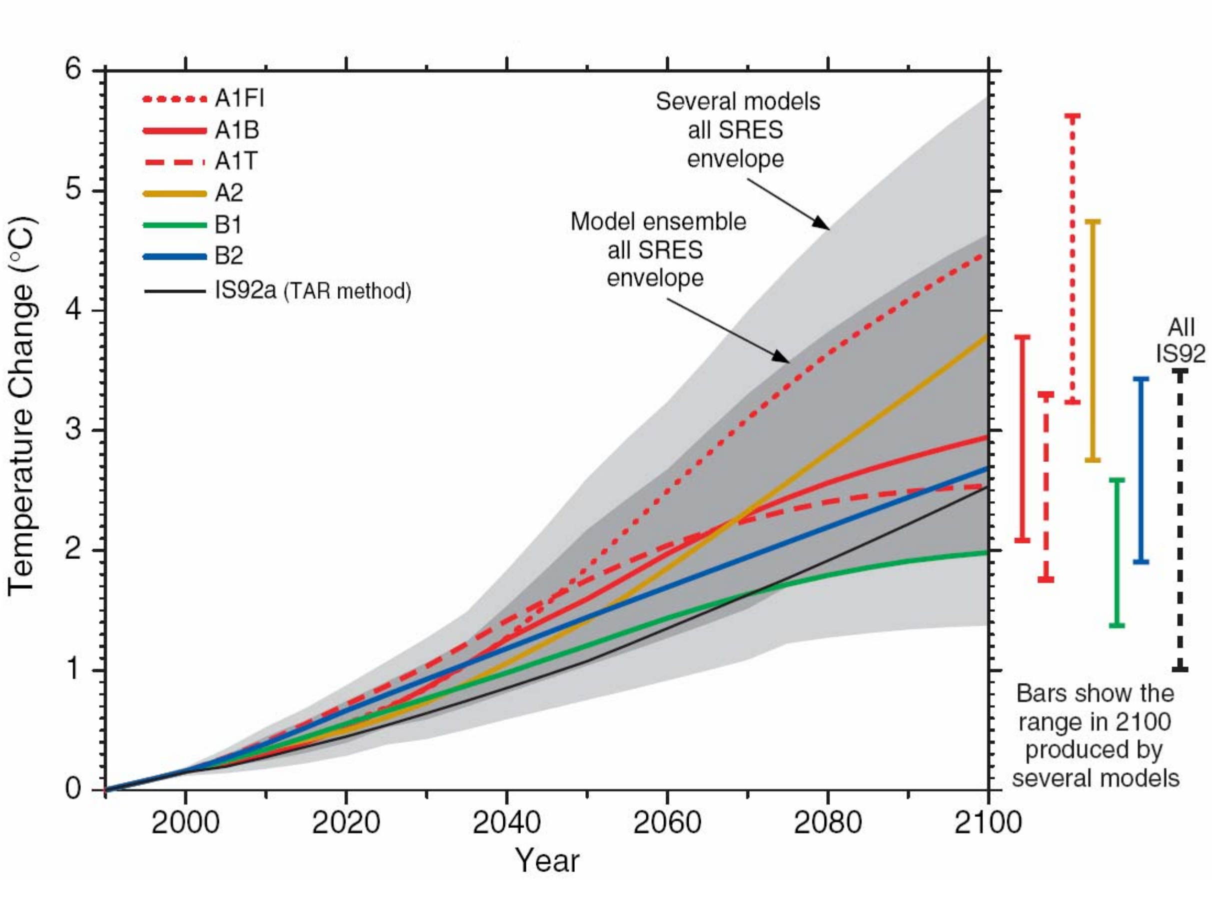

Figure 3. Global mean temperature projections for the six illustrative SRES scenarios using a simple climate model tuned to a number of complex models with a range of climate sensitivities. Also for comparison, following the same method, results are shown for IS92a. The darker shading represents the envelope of the full set of thirty-five SRES scenarios using the average of the models results. The lighter shading is the envelope based on all seven model projections (from IPCC, 2001).

The third major uncertainty is regional, described by changes to mean monthly rainfall and potential evaporation. To capture the ranges of these regional changes, we use projections from a range of international GCMs, as well as GCMs and Regional Climate Models (RCMs) developed by CSIRO.

Projections of regional climate change and model performance in simulating Queensland's climate have been described by Cai *et al.* (2003). Here, we have access to a similar suite of climate model results as summarised in Cai *et al.* (2003). They investigated the ability of the models to simulate sea level pressure, temperature and rainfall, discarding the four poorest-performing models from subsequent analysis. The models used for this study are summarised in Table 1.

Table 1. Climate model simulations analysed in this report. The non-CSIRO simulations may be found at the IPCC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk/). Note that D125 and CC50 are a regional climate models

Centre	Model	Emissions Scenarios post-1990 (historical forcing prior to 1990)	Years	Horizontal resolution (km)
CSIRIO, Aust	CC50	SRES A2	1961-2100	50
CSIRO, Aust	Mark2	IS92a	1881–2100	~400
CSRIO, Aust	Mark 3	SRES A2	1961-2100	~200
CSIRO, Aust	DARLAM125	IS92a	1961–2100	125
Canadian CC	CCCM1	IS92a	1961–2100	~400
DKRZ Germany	ECHAM4	IS92a	1990–2100	~300
Hadley Centre, UK	HadCM3	IS92a	1861–2099	~400
NCAR	NCAR	IS92a	1960-2099	~500
Hadley Centre, UK	HadCM3	SRES A1T	1950–2099	~400

Note: The HadCM3, ECHAM4 and CC50 Models were run for both medium and high climate sensitivities, all other models were run with medium climate sensitivity.

In the region surrounding the Fitzroy River Basin, annual rainfall projections range from slightly wetter, to much drier than the historical climate. Seasonally, changes are uncertain in DJF and to a lesser extent in MAM but are dominated by decreases in JJA and SON. Over successive generations of climate model, estimates of rainfall change have become drier, but increases in the Fitzroy River region remain plausible.

Regional temperature increases inland at rates slightly greater than the global average, with the high-resolution models showing the steepest gradient away from the coast. Ranges of change are shown in Cai *et al.* (2003). Changes to potential evaporation increases in all cases, with increases greatest when coinciding with significant rainfall decreases.

4.2. CLIMATE CHANGE PATTERNS

Patterns of climate change calculated as percentage change per degree of global warming were created for monthly changes in rainfall and point potential evaporation from a range of models. In OzClim, these are linearly interpolated onto a 0.25° grid (the simplest form of downscaling). Changes are averaged for a specific area.

Area average changes for the Nogoa catchment are shown in Table 2. All the models show increases in potential point evaporation, however increasing rainfall results in lesser increases in potential evaporation, an outcome that is physically consistent with having generally cloudier conditions in a situation where rainfall increases. This will produce a "double jeopardy" situation if mean rainfall decreases because this will be accompanied by relatively larger increases in potential evaporation.

Table 2. Changes in annual rainfall and point potential evaporation for the Nogoa catchment, simulated by the models in Table 1, expressed as a percentage change per degree of global warming

Model	Rainfall	Point Potential Evaporation
CCCM1	-2.55	5.84
DARLAM125	4.15	4.24
NCAR	2.10	3.70
MARK2	-5.21	5.26
ECHAM4	1.91	2.76
HADCM3 - IS92A	-5.46	8.21
HADCM3 - A1T	-5.42	8.14
CC50	-9.36	11.13
MARK3	-8.30	6.80

Seasonal changes are shown in Figure 4 where the mean monthly change for both rainfall and potential evaporation per degree of global warming is shown with the upper and lower extremes. Changes in potential evaporation are much more certain, always increasing and showing a slight inverse relationship with rainfall, with deviations of only few percent per degree of global warming between models.

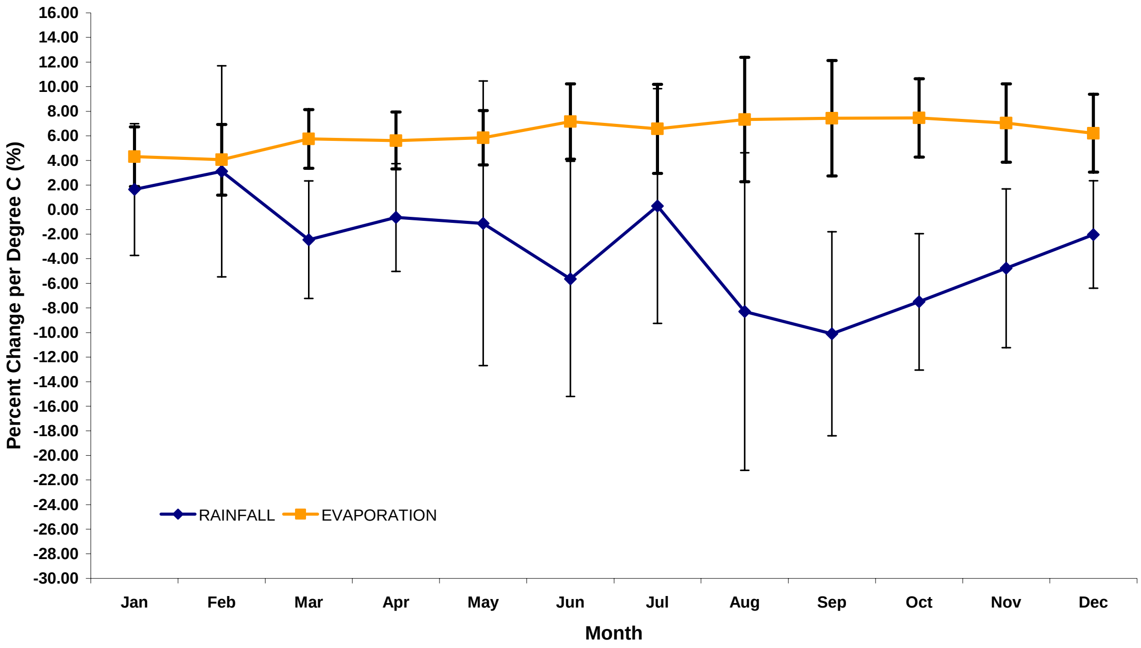

Figure 4. Average monthly percentage change in rainfall and potential evaporation for the Nogoa catchment (see Table 4 for the 10 locations) per degree of global warming using the nine climate models and emission scenarios with medium sensitivity shown in Table 1 with one standard deviation.

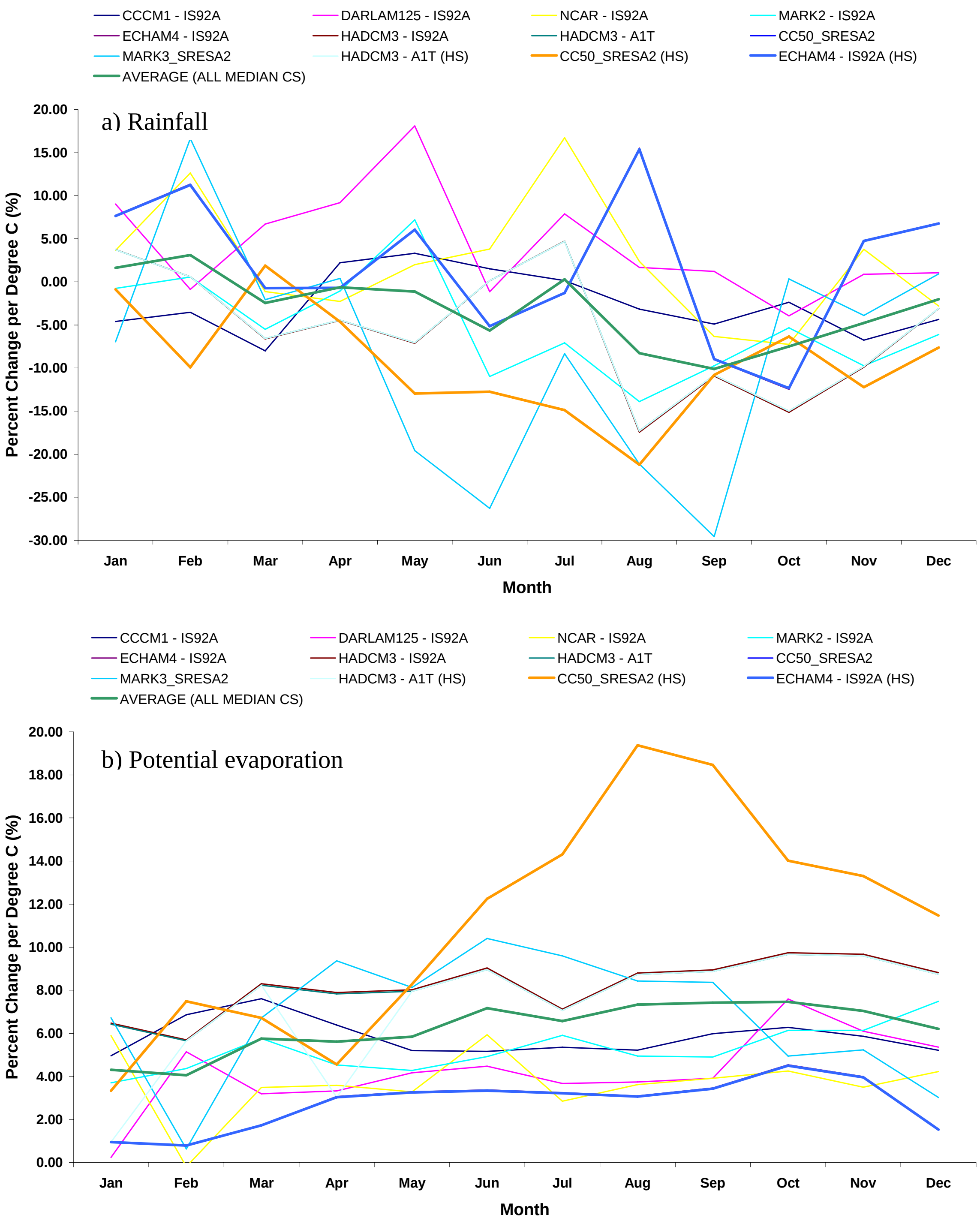

Figure 5. Average monthly percentage change in a) rainfall and b) potential evaporation for the Nogoa catchment (see Table 4 for the 10 locations) per degree of global warming for the nine climate models shown in Table 1 at medium (MS) and high sensitivity (HS).

4.3. CLIMATE CHANGE SCENARIOS

This report presents the range of possible changes provided by the dry, wet and average scenarios for the Nogoa catchment in 2030. This range combines the range of global warming from IPCC (2001) and the climate change patterns in Table 2..

The three scenarios are:

- A dry climate change scenario where global warming follows the SRES A2 greenhouse gas scenario in 2030 forced by high climate sensitivity with regional rainfall and potential evaporation changes expressed by the CC50 GCM.
- An average climate change scenario where global warming follows the average of all the climate models used in this analysis.
- A wet climate change scenario where global warming follows the IS92a greenhouse gas scenario in 2030 forced by high climate sensitivity, with regional rainfall and potential evaporation changes expressed by the German ECHAM4 GCM.

These simulations represent most of the possible ranges of change in average climate over the Nogoa catchment by 2030. Note that the dry and wet climate scenarios are both forced by high climate sensitivity. This is because in locations where either increases or decreases in rainfall are possible, the more the globe warms, the larger these accompanying regional changes will become. Therefore, if we wish to look at the extremes of possible changes in catchment response to climate change, then both the wet and dry scenarios will utilise the higher extreme of plausible global warming. These scenarios are summarised in Table 3.

Table 3. Dry, average and wet climate change scenarios for 2030 for the Nogoa catchment

Scenario	Dry	Average	Wet
Global warming scenario	SRES A2	Average of All	IS92a
GCM	CC50	Average of All	ECHAM4
Global mean warming (°C)	0.92	Average of All	0.78
Regional minimum temperature change (°C)	1.20	Average of All	0.90
Regional maximum temperature change (°C)	1.60	Average of All	0.90
Regional mean temperature change (°C)	1.40	Average of All	0.90
Change in annual rainfall (%)	-8.61	-2.36	1.47
Change in annual potential evaporation (%)	10.24	4.22	2.13

5. Natural resources and production in beef systems

5.1. MODEL CONSTRUCTION AND CALIBRATION

5.1.1. Climate change and CO_2 scenarios

Climate change scenarios were generated based on output from the CSIRO Mark 3 GCM. Changes in runoff, deep drainage, transpiration of pasture and trees, growth, basal area of pasture, stocking rate, live-weight gain and growth days were assessed for 2030. The projection was for 30 years, the equivalent of looking back 30 years from 2045. For the projection, combinations of higher (H) and lower (L) levels of predicted temperature (T) parameters (maximum temperature, minimum temperature, vapor pressure, evaporation, radiation, dew point) and rainfall (R) were generated to form four combinations that consisted of T-lower/R-lower (LL), T-lower/R-higher (LH), T-higher/R-lower (HL) and T-higher/R-higher (HH) (see Table 5, Appendix 1). For example, if the projection of rainfall change was -13% for 2030 then a -13% change was applied to the monthly rainfall record of 30 years.

An average CO_2 enrichment scenario was applied where the base CO_2 level in 1990 was about 355ppm, and in 2030 it was 452ppm. This was appropriate given the uncertainty of CO_2 response in terms of species effects, nitrogen supply and response of trees.

5.1.2. Location and pasture fertility

Climate change scenarios were drawn from the CSIRO Mark 3 GCM for Emerald (23^o31'S, 148^o10'E) in central Queensland. Mean annual rainfall is 648mm. The landscape type for the location was native pastures on a light textured soil of average fertility with no trees (AvCl).

5.1.3. Native pasture modelling

A perennial native grass model called GRASP was used to simulate a range of variables related to water balance, growth and animal production. A description of the equations is given in Littleboy and McKeon (1997) and the calibration and validation are described in Day *et al.* (1997). The parameter settings in the model for average fertility conditions without trees are shown in Table 4.

The changes to GRASP to incorporate CO_2 enrichment effects on pasture are described in detail by Howden *et al.* (1998a, b). In summary the following characteristics of C4 pasture growth were changed to represent atmospheric CO_2 levels of 452ppm in 2030 1) potential regrowth (kg DM/ha/day, +2.75%) 2) transpiration efficiency (kg DM/ha/mm @20hPa, +11%) 3) green yield at which potential transpiration is 50% of potential evapotranspiration (kg DM/ha, +11%) 4) rate of nitrogen uptake (kg N/ha per 100mm transpiration, +5.5%) and 5) radiation use efficiency (kg/ha per MJ/m^2, +1.375%). These CO_2 enrichment effects on pasture are conservative because they don't account for efficiency gains in nitrogen dilution and mineralisation of soil nitrogen that are likely under higher CO_2 levels.

The management of beef cattle steers simulated either 1) a constant stocking strategy (CSS) where a constant level of long-term average pasture growth was utilised annually by the cattle or 2) a responsive stocking strategy (RSS) where cattle numbers were adjusted to eat 10%, 20% and 40% of the pasture available at the 1st of June each year.

Table 4. Parameter values used in GRASP for average fertility without trees regime for Emerald

GRASP parameters	Parameter Number	Parameter Value
Potential regrowth per unit of grass basal area (GBC)	6	3.5
GBC per 1000 kg of yield	159	1.3
Transpiration efficiency @20hPa	7	13.5
Green yield at which potential trans is 50% of potential ET	45	1000
Soil water index (SWI) at which above ground growth stops	149	0.3
SWI required to support 100% of green cover	9	0.3
Maximum annual N uptake (kgN/ha)	99	20
Rate of N uptake in kgN/ha per 100mm transpiration	98	6
% N at which growth stops	101	0.68
Height of pasture at 1000 kg/ha	96	20
Radiation use efficiency kg/ha per MJ/m^2	8	12

5.1.4. Data analysis

An analysis of variance was used to compare the means for each of the measures across the grazing strategies, temperature/rainfall scenarios and utilisation levels. A multiple comparison procedure was used to determine which means were different – the Tukey's Honest Significant Difference method.

The cumulative distribution plots and box plots for each combination of the three factors are shown in Appendix 5 and 6.

5.2. RESULTS OF IMPACT ASSESSMENT

5.2.1. Rainfall and temperature

Climate change scenarios were generated based on output from the CSIRO Mark 3 GCM. Combinations of higher (H) and lower (L) levels of predicted temperature (T) and rainfall (R) were generated to form four combinations that consisted of T-lower/R-lower (LL), T-lower/R-higher (LH), T-higher/R-lower (HL) and T-higher/R-higher (HH) (see Appendix 1). The base climate used in the GRASP model from 1961-1990 was compared against climate adjusted for the period 2016-2045. The mean pre-1990 values for rainfall and temperature are shown in Table 5 with the adjustment factors for the 2030 climate.

Table 5. Mean pre-1990 rainfall and temperature for Emerald and the climate change factors for the lower (L) and upper (H) boundaries in 2030

Scenario	Rainfall (mm)	Rainfall change (%)	Max Temp (°C)	Max Temp change (°C)	Min Temp (°C)	Min Temp change (°C)
1990	612	0	29.6	0	15.7	0
2030 L	534	-13	29.7	0.1	15.9	0.2
2030 H	655	7	30.4	0.8	16.9	1.2

5.2.2. Runoff

Climate change scenarios had significant effects on runoff (Figure 6, Appendix 4, 5, 6). Low rainfall scenarios for 2030 produced lower mean runoff than 1990 (-17 to -23%, Appendix 3), whereas mean runoff for high rainfall scenarios and 1990 were similar (2-10%). Low and high temperature scenarios were not associated with different mean runoff, whereas low rainfall scenarios produced lower mean runoff than high rainfall scenarios.

Grazing strategy and utilisation level had significant effects on mean runoff. CSS produced lower mean runoff than RSS, and runoff increased with increasing utilisation of pasture.

The risk of climate change causing unmanageable increases in mean runoff in 2030 was low because the high rainfall scenario wasn't associated with more runoff than that currently experienced. Keeping stocking rates of livestock to sustainable levels (10-20% utilisation) will help maintain ground cover and continue to keep the risk of excessive runoff in 2030 low. High stocking rates (40% utilisation) increase the chance of high runoff causing soil erosion, loss of top soil and high sediment loads in waterways.

The low rainfall scenarios in 2030 were associated with lower mean runoff, reduced risk of excessive erosion events and reduced inflows into watercourses and dams. Water storages may need to be larger to capture more water from large, but less frequent, runoff events and water efficient methods applied that reduce evaporation, seepage and other wastage.

These analyses don't make provision for changes in the intensity of rainfall that is possible in some seasons under climate change conditions.

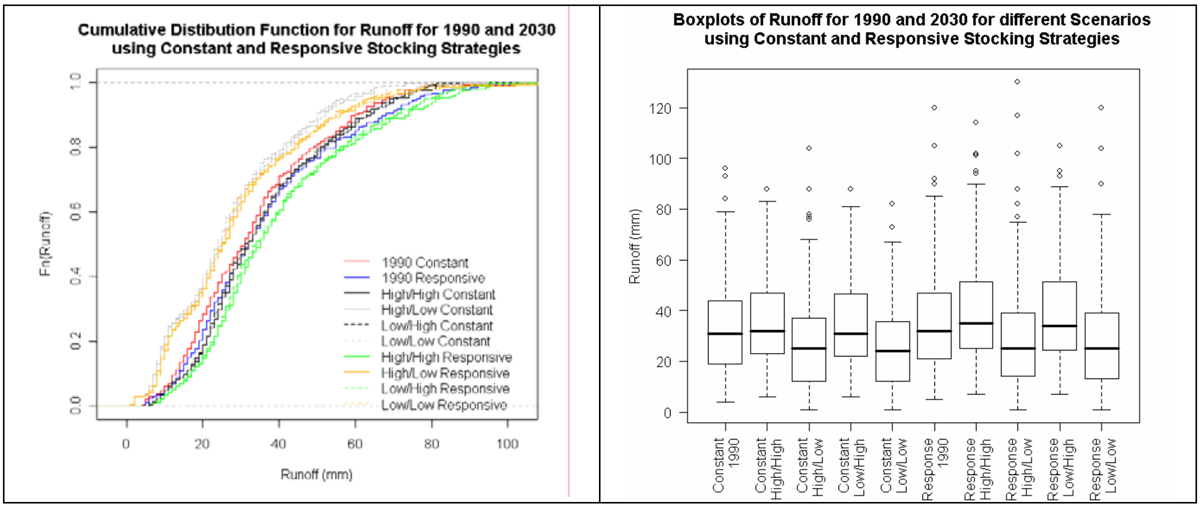

Figure 6. Runoff for 1990 and different temperature/rainfall scenarios for 2030 (HH, HL, LH, LL) for different stocking strategies (constant and responsive) across all utilisation levels shown using a cumulative distribution function and box plot.

5.2.3. Deep drainage – beyond 1 metre

Climate change scenarios had significant effects on deep drainage (Figure 7, Appendix 4, 5, 6). Low rainfall scenarios for 2030 produced lower mean deep drainage than 1990 (-37 to -44%, Appendix 3), whereas mean deep drainage for high rainfall scenarios and 1990 were similar (18-30%). Low and high temperature scenarios were not associated with different mean deep drainage, whereas low rainfall scenarios produced lower mean deep drainage than high rainfall scenarios.

The low rainfall climate change scenarios for 2030 reduced both the frequency and amount of water draining to 1 metre and beyond. This may reduce the threat of salinity but also limit water availability to deep rooted grasses, shrubs and trees. This may promote shallow rootedness and reduce drought tolerance of perennial vegetation. Maintaining a good basal grass cover may become more important to foster water infiltration at the soil surface and movement through the soil profile. The median deep drainage was near zero for low rainfall scenarios. The risk of high deep drainage levels under high rainfall scenarios is not different to that in 1990.

Grazing strategy and utilisation level had no effect on mean deep drainage.

These analyses don't make provision for changes in the intensity of rainfall that is possible in some seasons under climate change conditions.

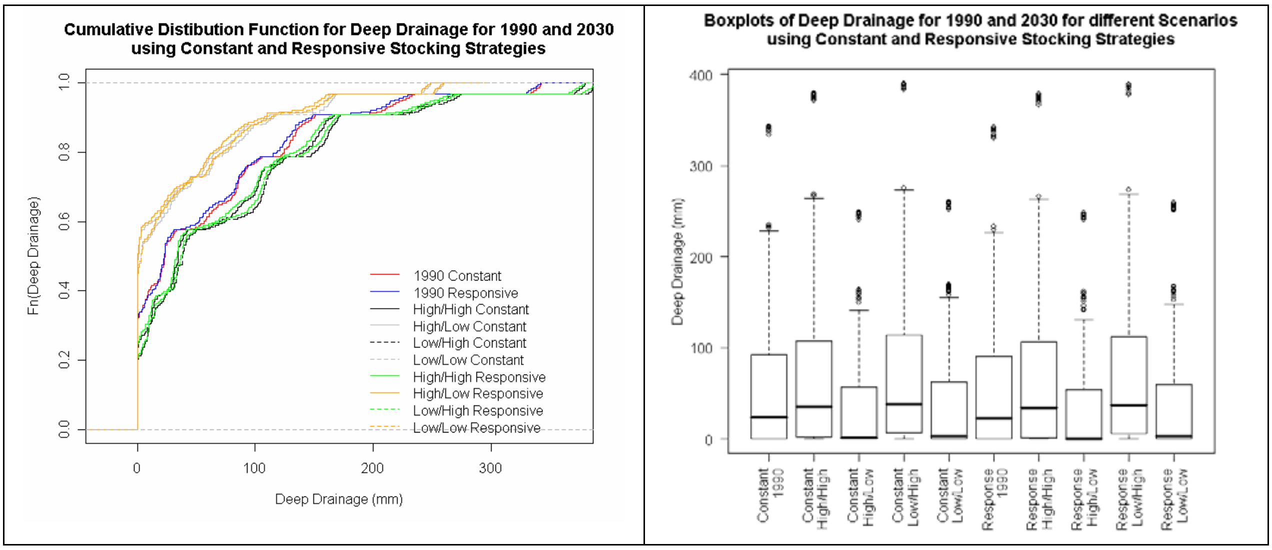

Figure 7. Deep drainage for 1990 and different temperature/rainfall scenarios for 2030 (HH, HL, LH, LL) for different stocking strategies (constant and responsive) across all utilisation levels shown using a cumulative distribution function and box plot.

5.2.4. Total standing dry matter (TSDM)

Climate change scenarios did not affect the mean TSDM compared to 1990 although there is likely to be increased risk of low TSDM (<1000 kg/ha) under low rainfall scenarios, and particularly under the high temperature/low rainfall scenario (Figure 8, Appendix 4, 5, 6).

The CSS was associated with higher TSDM than the RSS. This is because of the difference in the way the two stocking strategies annually allocate stock numbers. The CSS uses average long-term pasture growth and applies the utilisation level (10%, 20% or 40% in this study) to determine the stocking rate. For example, an average long-term annual growth of 2500 kg/ha utilising 20% per annum would mean that 500 kg/ha is available for animals. Using an average annual intake of cattle of 3200 kg then the CSS stocking rate is 500/3200 or 0.15 AE/ha. This stocking rate is applied each year so in years when the growth is more than 2500 kg/ha the actual utilisation of pasture is below 20%.

The RSS adjusts the cattle numbers annually to utilise (or consume) a proportion (10%, 20% or 40%) of the pasture available on the 1st of June each year after most of the annual growth has occurred following the main summer growing season. Because the available pasture includes growth from the current season plus that remaining from previous years, the RSS method usually calculates higher stocking rates than CSS. As a result TSDM is lower in RSS than CSS. These differences between the two stocking strategies do not mean that one is less sustainable than the other, but RSS does require a more active management approach with greater annual trading of animals because of the high annual variability in pasture growth.

The CSS was associated with similar amounts of TSDM for 1990 and the low and high rainfall scenarios in wet years (TSDM >2500 kg/ha). This was because the CSS method under-utilises the pasture in wet years of high growth leaving more TSDM.

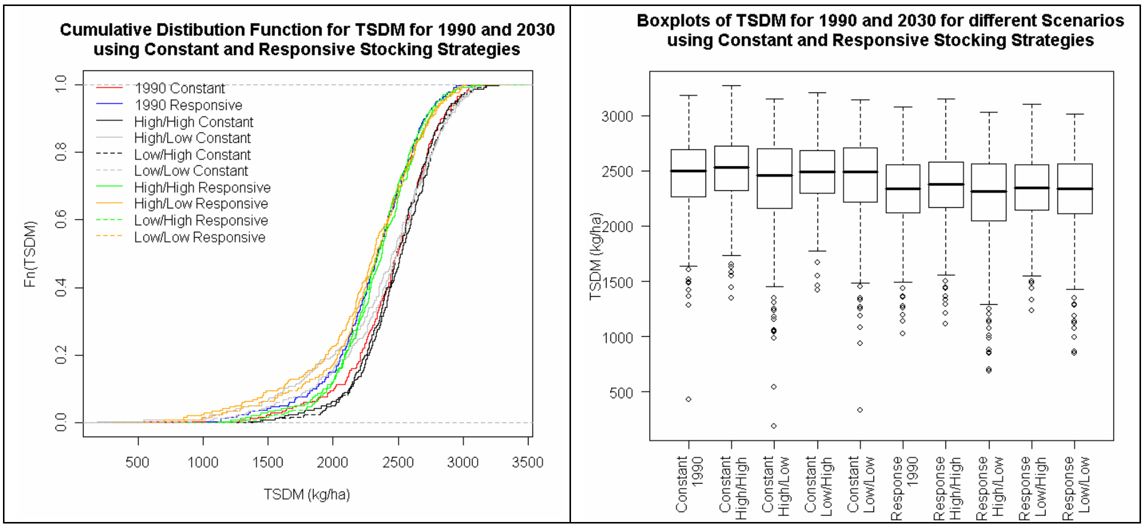

Figure 8. Total standing dry matter (TSDM) for 1990 and different temperature/rainfall scenarios for 2030 (HH, HL, LH, LL) for different stocking strategies (constant and responsive) across all utilisation levels shown using a cumulative distribution function and box plot.

5.2.5. Basal area

Climate change scenarios had significant effects on basal area (Figure 9, Appendix 4, 5, 6). Low rainfall scenarios for 2030 were associated with lower mean basal area than 1990 (-11%, Appendix 3) and high rainfall scenarios produced higher mean basal area than 1990 (5%). Low and high temperature scenarios were not associated with different mean basal area, whereas low rainfall scenarios produced lower mean basal area than high rainfall scenarios.

The low rainfall climate change scenario was associated with an overall reduction in basal area of about 10% by 2030. The risk of a basal area of <2.5% occurring will rise from near zero in 1990 to about 1 in every 3 years by 2030. Low basal area exposes the soil surface, increases the risk of erosion and decreases water infiltration into the soil. Maintaining a good basal grass cover will become more important to foster water infiltration at the soil surface and movement of water through the soil profile.

Keeping stocking rates of livestock to sustainable levels (10-20% utilisation) will help maintain ground cover (sum of basal area, pasture canopy cover and litter cover) and continue to help reduce the risk of excessive runoff and poor infiltration in 2030. High stocking rates (40% utilisation) reduce the amount of ground cover and increase the chance of poor water infiltration, high runoff and loss of top soil and high sediment loads in waterways.

The high rainfall climate change scenario was associated with an overall increase in basal area of around 5% by 2030.

Grazing strategy and utilisation level had no effect on basal area.

These analyses don't make provision for changes in the intensity of rainfall that is possible in some seasons under climate change conditions.

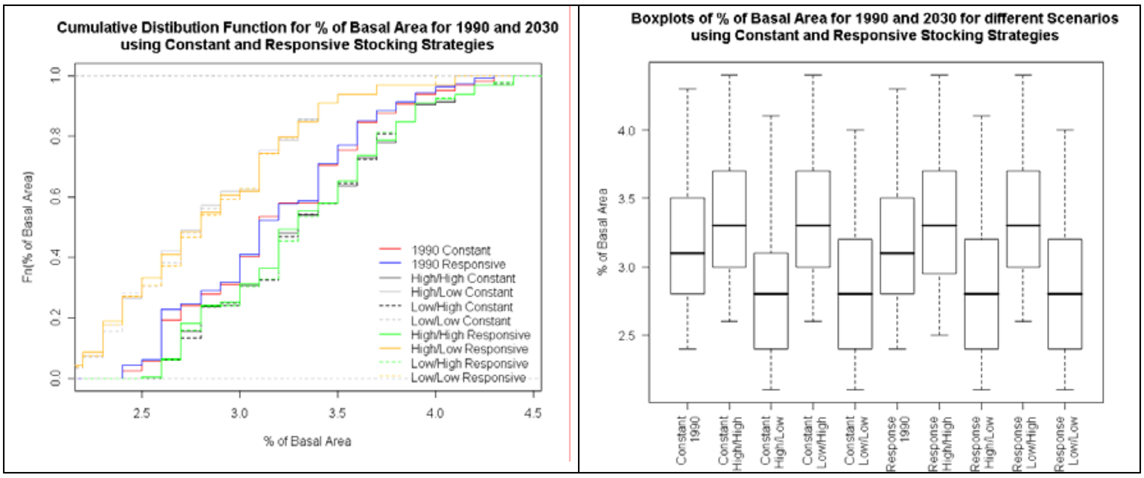

Figure 9. Basal area percentage for 1990 and different temperature/rainfall scenarios for 2030 (HH, HL, LH, LL) for different stocking strategies (constant and responsive) across all utilisation levels shown using a cumulative distribution function and box plot.

5.2.6. Live weight gain per head

Climate change scenarios had significant effects on mean LWG/hd (Figure 10, Appendix 4, 5, 6) however only the high temperature/high rainfall scenario was significantly different to 1990 (5%). This difference occurring for HH and not LH suggests that, when rainfall was not limiting, the high temperature scenario triggered a response in the pasture that produced significantly more LWG/hd. When rainfall was not limiting the high temperature scenario was sufficient to lengthen the growing season during winter, increase annual growth and LWG/hd. This was likely because the extra growth is green and of high quality, and it provides added nutrition to animals during the annual dry period.

Stocking strategy and utilisation level had a significant effect on LWG/hd. CSS was associated with a higher mean LWG/hd than RSS. The stocking strategy appeared to influence LWG/hd more than climate change. Lower utilisation was associated with higher LWG/hd.

The low rainfall climate change scenarios were associated with an increase in risk of low annual LWG/hd by 2030. The risk of a LWG/hd of <140 kg/hd/yr in 1990 was <10% whereas in 2030 this risk was nearly 20% under the low rainfall scenarios. The risk of <140 kg/hd/yr under high rainfall scenarios was similar to 1990. The high rainfall scenarios were associated with a higher overall LWG/hd compared to 1990. This opportunity was more attainable with CSS than RSS.

The low rainfall climate change scenarios were associated with higher variability of LWG/hd. This variability increased with increased utilisation level. Maintaining stocking rates at sustainable levels (10-20% utilisation) will maintain the efficiency of live weight gain and be a useful tactic in managing the greater variability of production expected under low rainfall climate change conditions.

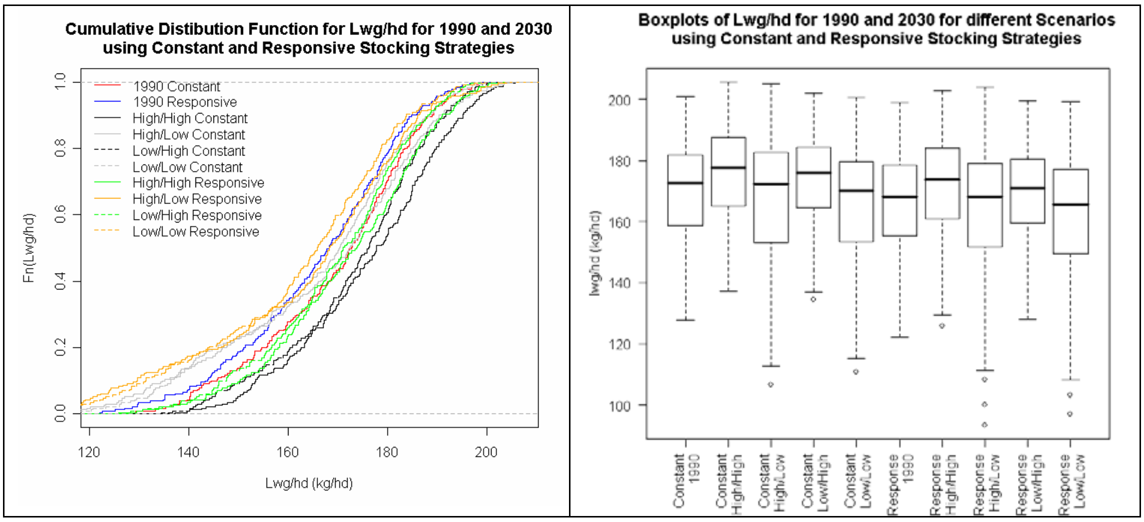

Figure 10. Live weight gain per head for 1990 and different temperature/rainfall scenarios for 2030 (HH, HL, LH, LL) for different stocking strategies (constant and responsive) across all utilisation levels shown using a cumulative distribution function and box plot.

5.2.7. Live weight gain per hectare

Live weight gain per hectare is a function of live weight gain per head and stocking (or utilisation) rate. Therefore LWG/ha was closely associated with the level of target utilisation and because in wetter than normal years RSS generates higher actual utilisation levels than CSS (see 4.2.5) the RSS was associated with higher LWG/ha than CSS (Figure 11, Appendix 4, 5, 6). This association occurred for 1990 and the climate change scenarios.

At the optimum level of utilisation (36%) the CSS produced 38 kg LWG/ha. This was not different under climate change conditions. The RSS produced 46 kg LWG/ha at an optimum utilisation level of 42% in 1990 and 48% in 2030. However the higher production of RSS compared to CSS may have adverse effects on resources when utilisation levels are maintained at high levels (>40%).

Under field conditions LWG/ha increases with utilisation level until the reduction in availability of green pasture for stock has a negative impact and LWG/ha declines. This process is represented in the model (see Appendix 7g). Another field process that is not currently represented in the model is a negative feedback on LWG/ha from high utilisation levels on pasture recovery. High levels of utilisation (>40%), particularly during drought, have adverse effects on pastures, increase recovery time after drought, delay restocking and reduce animal production. This negative feedback process is not currently built into the model, and as such, LWG/ha at high utilisation levels may be overestimated.

Climate change scenarios had significant effects on mean LWG/ha (Figure 12, Appendix 4, 5, 6) however only the high temperature/high rainfall scenario was significantly different to 1990 (6%). This difference occurred for HH and not LH, which was similar to LWG/hd, and is related to an increase in the length of the pasture growing season during winter which was sufficient to improve LWG/hd (see 4.2.7).

Low rainfall scenarios were associated with lower LWG/ha in dry years using a RSS compared to 1990. This was particularly evident at 40% utilisation and is associated with higher selection pressure and lower availability of green pasture during dry years. Under low rainfall climate change conditions low utilisation levels during drier than normal years will reduce the risk of large reductions in LWG/ha using RSS.

A CSS was associated with less animal production risk in drought years (< decile 10) than RSS for all climate change scenarios but for the remainder of the rainfall distribution (> decile 10) LWG/ha was greater for RSS.

The high rainfall scenarios were associated with a higher LWG/ha, but mainly associated with the drier than normal years and particularly with the RSS rather than CSS. In the wetter than normal years a build up of nitrogen in the soil associated with low rainfall scenarios in dry years ensures greater availability of nitrogen compared to high rainfall scenarios when rainfall is not limiting. Under these circumstances low rainfall scenarios can produce greater growth than high rainfall scenarios in the wetter years because of an ‘unlimited’ nitrogen supply in the soil.

Climate change did not significantly increase the animal production risk beyond the variability currently generated by stocking strategy and utilisation level. However individual land managers may need to adapt by altering the mix of stocking strategies or changing utilisation of pasture to better suit the changing climatic conditions.

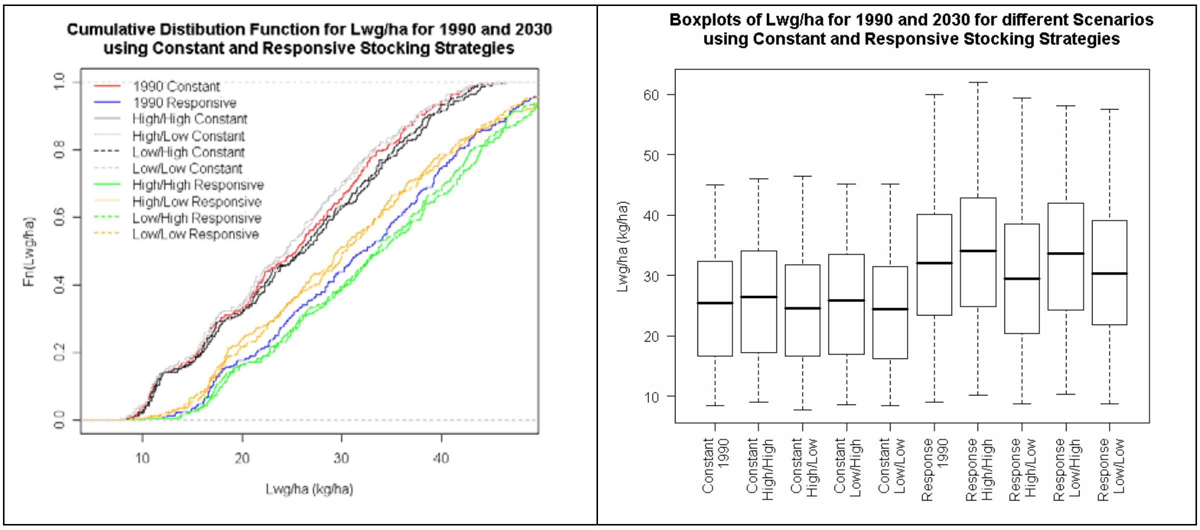

Figure 11. Liveweight gain per hectare for 1990 and different temperature/rainfall scenarios for 2030 (HH, HL, LH, LL) for different stocking strategies (constant and responsive) across all utilisation levels shown using a cumulative distribution function and box plot.

5.2.8. Growth

Climate change scenarios did not effect the mean growth of pasture compared to 1990 although variability of annual growth increased under low rainfall scenarios, and particularly under the high temperature/low rainfall scenario (Figure 12, Appendix 4, 5, 6). The higher variability of growth between years under low rainfall compared to 1990 and high rainfall scenarios is associated with greater under-use of available nitrogen in dry years, more nitrogen build up in the soil and relatively more nitrogen being available for growth in wet years.

The higher variability of annual growth under low rainfall scenarios will make it more difficult to sustainably manage stocking rate. Larger differences in year-to-year growth will make it more difficult to fully adopt a RSS because more animals will need to be traded annually. A CSS fails to take advantage of abundant pasture reserves in wet years but allows for recovery of pastures that is necessary after long dry periods. Finding the balance between utilising pastures for animal production and leaving them understocked for recovery will become more difficult and better tools are needed to help pastoralists assess pasture quantity and quality, sustainable stocking rates and recovery times of pastures.

The risk of less than 1500 kg/ha of annual growth is increased under the low rainfall scenarios. This heightened risk of drought may force changes in drought policy, cause changes in enterprise mix (e.g. grain to grazing, grazing to feedlots) and animal species (more *Bos indicus* cattle, possibly with sheep), early destocking practices, increase size of viable properties, prolong pasture recovery phases and increase the risk of land ownership on low equity rates. More droughts may also reduce the incidence and prevalence of parasites (e.g. cattle tick) and disease.

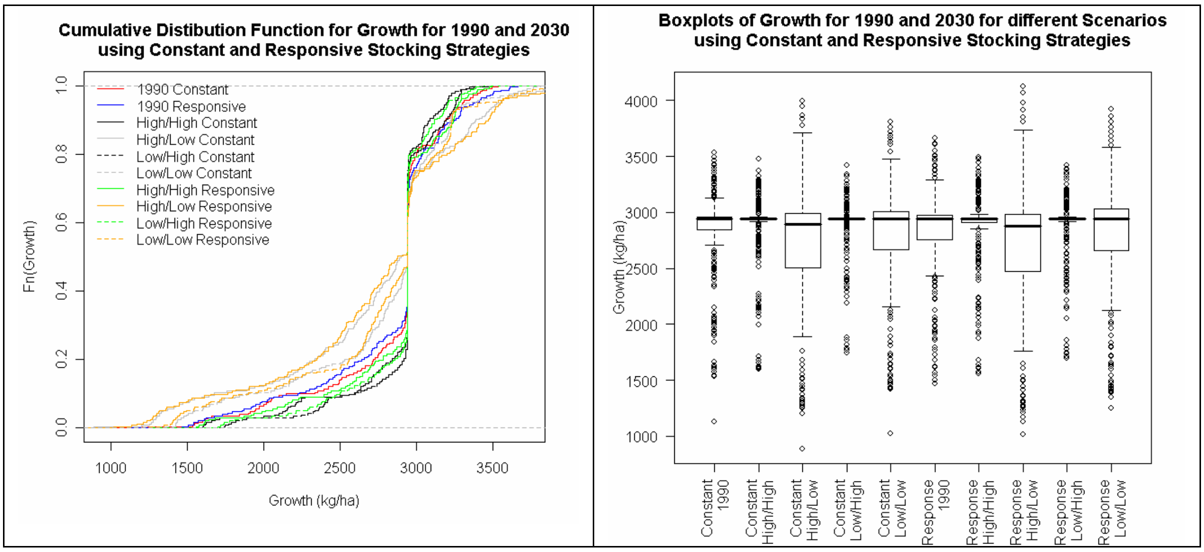

Figure 12. Growth for 1990 and different temperature/rainfall scenarios for 2030 (HH, HL, LH, LL) for different stocking strategies (constant and responsive) across all utilisation levels shown using a cumulative distribution function and box plot.

Grazing strategy and utilisation level did not effect mean annual growth.

The high rainfall scenarios were associated with lower annual variability in pasture growth. Higher rainfall can only produce more growth when nitrogen is not limiting so the application of exogenous sources (e.g. fertilizer, legumes) will need further economic investigation under these circumstances. The use of seasonal rainfall forecasting will be important and the economic implications of fertilizer application may depend on the accuracy of the forecast.

The high temperature scenarios (for CSS and RSS) produced more growth during wet years than low temperature scenarios (for both high and low rainfall scenarios). This difference was reversed during dry years. When rainfall was not limiting the high temperature scenario was sufficient to lengthen the growing season during winter and increase annual growth. When rainfall was limiting the high temperature scenario exacerbated moisture stress and lowered growth.

High utilisation levels in wet years were associated with more growth, but in dry years high utilisation levels produced lower growth for a given amount of rainfall (Appendix 7c). Highlighted years show those with the highest rainfall in the historical record which produced the highest growth.

The vertical nature of the cumulative distribution function plot (Figure 8) around the median is a reflection of nitrogen unavailability limiting the growth of pasture in many years associated with around median rainfall. Higher than median growth occurs in wet years that follow one or more dry years in which the available nitrogen is not fully used, it builds up in the soil and is subsequently available for pasture growth in latter years.

6. Conclusions and recommendations

6.1. SUMMARY OF THE RISK ASSESSMENT

The following management is suggested as a useful means of managing climate variability and adapting to climate change:

1. Keeping stocking rates of livestock to sustainable levels (10-20% utilisation) will help maintain ground cover and continue to keep the risk of excessive runoff in 2030 low.
2. Water storages may need to be larger to capture more water from large, but less frequent, runoff events and water efficient methods applied that reduce evaporation, seepage and other wastage.
3. Maintaining a good basal grass cover may become more important to foster water infiltration at the soil surface and movement through the soil profile.
4. The higher variability of pasture growth will make it more difficult to sustainably manage stocking rate. Finding the balance between utilising pastures for animal production and leaving them understocked for recovery will become more difficult and better tools are needed to help pastoralists assess pasture quantity and quality, sustainable stocking rates and recovery times of pastures.
5. The heightened risk of drought may force changes in drought policy, cause changes in enterprise mix (e.g. grain to grazing, grazing to feedlots) and animal species (more *Bos indicus* cattle, possibly with sheep), early destocking practices, increase size of viable properties, prolong pasture recovery phases and increase the risk of land ownership on low equity rates. More droughts may also reduce the incidence and prevalence of parasites (e.g. cattle tick) and disease.
6. The application of exogenous sources (e.g. fertilizer, legumes) will need further economic investigation under climate change circumstances.
7. The use of seasonal rainfall forecasting will be important and the economic implications of management decisions (e.g. fertilizer application) may depend on the accuracy of climate forecasts.
8. Maintaining stocking rates at sustainable levels (10-20% utilisation) will maintain the efficiency of live weight gain and be a useful tactic in managing the greater variability of production expected under low rainfall climate change conditions.
9. Individual land managers may need to adapt by altering the mix of stocking strategies or changing utilisation of pasture to better suit the changing climatic conditions. They will need training and tools to help assess pasture biomass and quality, forecast rainfall and pasture growth, adjust utilisation of pastures and balance production and resource priorities to ensure profitable and sustainable pastoral industries.

6.2. LIMITATIONS OF THE ASSESSMENT

There are a number of limitations in this assessment that will affect the interpretation and application of its results. These limitations concern:

- uncertainty linked to the greenhouse effect;
- the limitations of climate modelling, which affect how subsequent output can be used,
- the method of scenario construction,
- the application of those scenarios to the impact model,
- the relationship between climate change and ongoing climate variability, and
- pasture model uncertainties.

6.2.1. Greenhouse-related uncertainties

Climate change uncertainties can be divided into scientific uncertainties and socio-economic uncertainties. Many scientific and some socio-economic uncertainties can be reduced by improved knowledge that can be simulated within models. Some uncertainties are irreducible; for example, the chaotic behaviour of systems or future actions of people affecting rates of greenhouse gas emissions. Some uncertainties will be reduced through human agency; for example adaptation to reduce the impacts of climate change or the mitigation of climate change through greenhouse gas reductions.

In this report, the major greenhouse-related uncertainties we have accounted for are climate sensitivity (model sensitivity to atmospheric radiative forcing), regional climate change (managed by using a suite of climate models providing a range of regional changes) and a non-fossil fuel greenhouse gas scenario (the A1T SRES scenario).

6.2.2. Climate model limitations

The main limitations of climate models, apart from incomplete knowledge, which is addressed above, relates to scale. Much of the variability within the real climate is emergent from very fine-scaled processes that may not be well represented in climate models, particularly those models with coarser resolution. The two major limitations relate to changes in the interannual and daily variability of rainfall. A further limitation relates to the coarse resolution of topography, not thought to be a major contributor to regional uncertainty over most of Australia. Incomplete or partially known physical processes also limit climate models – the most significant of those being limited to the behaviour of clouds under climate change, which contributes to climate model sensitivity, mentioned in the previous section.

Interannual rainfall variability is subject to large scale teleconnections, and so requires fully coupled climate models of sufficient vertical and horizontal resolution to be adequately simulated. However there is as yet no real agreement between different models as to how important phenomena, such as the El Niño – Southern Oscillation phenomenon may behave under climate change. Each rain event is also limited in scale to the size of the grid spacing in the model. Essentially, each rain event occurs across a whole grid box, which tends to reduce its intensity because fine-scale convection processes cannot easily be produced. Therefore, although climate models indicate increases in daily rainfall intensity, these increases are generally under-estimated under all but the finest resolution regional models. Methods are currently being explored to combine both global and local influences in fine scale model simulations but as yet this data is not available for impact studies. However, a few specialised climate runs would also fail to properly address a range of uncertainties that a larger set of models can provide. This is one reason why we have not traditionally relied heavily on downscaled rainfall data.

6.2.3. Scenario construction methods

Climate scenario construction needs to strike a balance between representing a realistic set of changes and uncertainty using available resources. Rainfall is the main driver in simulating hydrological change and can potentially change across a range of temporal and spatial scales. Obviously, it is difficult to produce scenarios that represent all changes that a model can realistically simulate or to compensate for those changes where model simulations indicate a change but where the output cannot be used directly (as in downscaling).

In this project, we used the OzClim climate scenario generator which has climate change patterns from a number of different models installed: most importantly for this project, monthly patterns of change per degree of global warming for average rainfall and potential evapotranspiration. These patterns contain normalised representations of local change as a function of global warming that can be re-scaled using a wide range of average global warming to provide changes representing the outcomes for each climate model for any date from 1990 to 2100. This method is valid for the range of global warming provided by IPCC (2001). Therefore, by using a range of climate models we are representing as wide a range of local climate change that can reliably be quantified.

However, changes to climate variability have not been explicitly represented in these scenarios. This would require access to large volumes of high-resolution data and likely involve intensive downscaling methods for data from many models, which we do not have the resources to undertake.

6.2.4. Scenario application

The method of scenario application we have used is to multiply daily changes in rainfall and potential evaporation by a single monthly value of percentage change, the so-called uniform perturbation method. This assumes that all values within that month will change by the same amount e.g. -5%, without any changes in daily variability.

Studies of daily rainfall output from climate models indicate that extreme rainfall is likely to increase, except where decreases in the mean are large. The number of raindays appears likely to decrease, except for larger increases in rainfall. Even for situations where mean rainfall does not change, climate models indicate increases in extreme falls and a decrease in lighter falls and the number of rain days. As detailed in the previous section, we do not have the resources to test the impacts of such changes.

The application of changes in monthly mean to historical daily data means that changes in annual and seasonal mean rainfall are well represented, but not differential changes in daily rainfall or the number of raindays. Where such changes have been simulated from CSIRO Mark2 data, they produce increases of several percent (Chiew *et al.* 2003) but this rainfall output was not downscaled further, which would increase the simulated intensities of the heaviest falls.

The perturbation of historical data also means that interannual variability is largely preserved (it is altered somewhat by interseasonal changes), so the underlying assumption is that the pattern of dry and wet years will not be greatly altered under climate change. (There is no compelling reason from the investigation of climate model data to either confirm or deny this). This is one reason why long time series of historical data are preferred, so that a reasonable sample of climate variability can be assessed for potential change.

6.2.5. Climate change and variability

The method of scenario application used in this study does not incorporate longer-term changes in climate variability that have been known to occur in the past, beyond those contained in the baseline data. Abrupt changes in rainfall regime affecting both means and variability are known to occur several decades apart but the dynamics of these changes are not well understood and as yet are unpredictable.

6.2.6. Pasture growth model uncertainties

Rainfall changes had a larger influence than temperature. Most of the climate change in Queenslands grazing lands up to 2001 has been increases in minimum temperatures, with little change in radiation, evaporation and vapor pressure deficit resulting in minor changes for plant growth in the tropics (see Torok and Nicholls 1996, McKeon *et al.* 1998, McKeon *et al.* 1993). However, projections of this change may increase the length of the growing season in the mid latitudes for tropical native pastures during the winter months.

Since 2001, and in 2002 in particular, large increases in maximum temperature occurred which increases vapor pressure deficit, which significantly reduces plant growth.

These climate change scenarios do not include changes in wind speed, which may be related to depletion of ozone over Antarctica producing semi-permanent highs and reduced winds. Reduced wind may mitigate the effects of global warming from a plant growth viewpoint.

The occurrence of tropical cyclones and intense rainfall events has not been considered in these analyses.

6.3. RECOMMENDATIONS

Recommendations for further research include:

- Compare the capacity of grazing management practices at the paddock/farm/catchment scale to maintain ground cover and basal area; limit runoff, soil loss and sediment loads; by coupling biophysical and hydrological models.
- Identify important natural resource and agricultural thresholds in a changing climate and investigate the adaptive capacity of planning and management.
- Investigate modes of decadal rainfall variability for the region.
- Investigate how NRM planning responds to changes in climate that may be beyond the coping range of natural resource managers.
- Assess current land use strategies in light of possible changes.
- Identify differential changes in daily rainfall and number of raindays using finer resolution climate models to assess the impact of changes in rainfall intensity and timing.

7. Acknowledgements

This work was funded by the Australian Greenhouse Office. The Department of Primary Industries supported this project though most of its life before it was transferred to the Department of Natural Resources and Water. Greg McKeon helped with configuring the pasture model to run the climate change scenarios.

8. Publications

An abstract has been submitted and accepted for the MODSIM 2007 Conference in New Zealand titled *Climate change impacts on the sediment load for the Nogoa catchment of the Fitzroy Basin*.

Abstracts have been submitted to the joint International Grasslands and Rangelands Congress in China in June 2008 titled *Land use change and impacts of climate change on sediment load in the Fitzroy Basin* and *Impacts and adaptation to climate change in beef production systems in central Queensland*.

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Appendix 1. **Climate change scenarios (actual values and difference) in central Queensland for benchmark climate (Cc), and lower (L) and upper (H) boundaries in 2030.**

	Emerald	Emerald Difference
Rainfall (mm)		
Cc	612	0%
30L	534	-13%
30H	655	7%
Maximum temperature (^{O}C)		
Cc	29.6	0
30L	29.7	0.1
30H	30.4	0.8
Minimum temperature (^{O}C)		
Cc	15.7	0
30L	15.9	0.2
30H	16.9	1.2
Vapor pressure		
Cc	16.6	0
30L	16.7	0.1
30H	17.1	0.5
Evaporation		
Cc	5.8	0
30L	5.8	0
30H	6.1	0.3
Radiation		
Cc	20.1	0
30L	20.2	0.1
30H	20.6	0.5
Dew point		
Cc		0
30L		0.067
30H		0.335

Appendix 2. **Benchmark (control) values and values for different climate change scenarios for Emerald with average fertilisation and no trees**

			1990	2030			
			Control	hh	hl	lh	ll
Stocking Strategy	**Utilisation**	**Data**					
Constant	10%	Growth	2860	2883	2793	2893	2821
		Runoff	27	30	21	29	21
		Drain4	65	76	37	81	40
		Tsdm	2762	2795	2732	2777	2749
		%basal	3.2	3.4	2.9	3.4	2.9
		Lwg/hd	178	184	177	181	175
		Lwg/ha	11	11	11	11	10
	20%	Growth	2860	2878	2768	2887	2802
		Runoff	30	33	24	33	24
		Drain4	63	74	36	79	39
		Tsdm	2562	2604	2500	2585	2533
		%basal	3.2	3.3	2.9	3.3	2.9
		Lwg/hd	173	179	171	176	169
		Lwg/ha	21	21	20	21	20
	40%	Growth	2781	2869	2640	2868	2689
		Runoff	43	44	36	44	34
		Drain4	56	68	31	72	35
		Tsdm	2099	2192	1984	2172	2042
		%basal	3.1	3.3	2.8	3.3	2.8
		Lwg/hd	161	169	156	166	156
		Lwg/ha	38	40	37	39	37
Responsive	10%	Growth	2855	2880	2776	2890	2811
		Runoff	29	32	22	31	22
		Drain4	63	75	37	80	40
		Tsdm	2653	2688	2615	2670	2639
		%basal	3.2	3.4	2.9	3.4	2.9
		Lwg/hd	175	181	174	178	171
		Lwg/ha	16	17	16	17	16
	20%	Growth	2843	2871	2746	2882	2790
		Runoff	34	37	27	36	26
		Drain4	61	72	34	77	38
		Tsdm	2398	2435	2339	2423	2377
		%basal	3.2	3.3	2.9	3.3	2.9
		Lwg/hd	168	174	167	172	165
		Lwg/ha	28	30	27	29	27
	40%	Growth	2802	2844	2665	2859	2730
		Runoff	45	49	37	48	36
		Drain4	54	65	29	70	32
		Tsdm	1998	2041	1914	2038	1967
		%basal	3.2	3.3	2.8	3.3	2.8
		Lwg/hd	158	164	154	162	153
		Lwg/ha	45	47	42	46	42

Appendix 3. Average benchmark values and percentage change from benchmark (control) for different climate change scenarios for Emerald with average fertility and no trees

			1990	2030			
			Control	Hh	hl	lh	Ll
Stocking Strategy	**Utilisation**	**Data**					
Constant	10%	Growth	2860	1	-2	1	-1
		Runoff	27	10	-22	8	-23
		Drain4	65	18	-42	26	-37
		Tsdm	2762	1	-1	1	0
		%basal	3	4	-11	4	-11
		Lwg/hd	178	4	0	2	-2
		Lwg/ha	11	3	-1	2	-2
	20%	Growth	2860	1	-3	1	-2
		Runoff	30	9	-21	7	-22
		Drain4	63	19	-43	26	-38
		Tsdm	2562	2	-2	1	-1
		%basal	3	5	-11	5	-10
		Lwg/hd	173	4	-1	2	-2
		Lwg/ha	21	4	-1	2	-2
	40%	Growth	2781	3	-5	3	-3
		Runoff	43	3	-17	2	-20
		Drain4	56	22	-44	30	-37
		Tsdm	2099	4	-5	3	-3
		%basal	3	5	-11	5	-11
		Lwg/hd	161	5	-3	3	-3
		Lwg/ha	38	5	-3	3	-3
Responsive	10%	Growth	2855	1	-3	1	-2
		Runoff	29	10	-22	8	-23
		Drain4	63	19	-42	26	-37
		Tsdm	2653	1	-1	1	-1
		%basal	3	4	-11	5	-10
		Lwg/hd	175	3	-1	2	-2
		Lwg/ha	16	5	-2	2	-2
	20%	Growth	2843	1	-3	1	-2
		Runoff	34	10	-20	8	-22
		Drain4	61	19	-43	27	-38
		Tsdm	2398	2	-2	1	-1
		%basal	3	5	-11	5	-10
		Lwg/hd	168	4	-1	2	-2
		Lwg/ha	28	5	-3	3	-3
	40%	Growth	2802	1	-5	2	-3
		Runoff	45	9	-19	6	-21
		Drain4	54	20	-46	29	-40
		Tsdm	1998	2	-4	2	-2
		%basal	3	4	-11	5	-11
		Lwg/hd	158	4	-3	2	-3
		Lwg/ha	45	6	-7	4	-5

Appendix 4. ANOVA's for runoff, deep drainage, basal area, growth, TSDM, LWG/hd and LWG/ha

Runoff

	DF	Sum Sq	Mean Sq	F-Value	P-Value	Significant at
Stocking Strategy	1	1566	1566	4.5249	0.03365	0.05
Temp/Rain	4	19529	4882	14.1103	3.35E-11	0.001
Utilisation	2	41479	20739	59.9385	< 2.2e-16	0.001
Residuals	982	339784	346			

Deep Drainage

	DF	Sum Sq	Mean Sq	F-Value	P-Value	Significant at
Stocking Strategy	1	689	689	0.1189	0.7303	
Temp/Rain	4	301677	75419	13.0112	2.50E-10	0.001
Utilisation	2	11290	5645	0.9739	0.378	
Residuals	982	5692138	5796			

% of Basal Area

	DF	Sum Sq	Mean Sq	F-Value	P-Value	Significant at
Stocking Strategy	1	0.002	0.002	0.0101	0.9201	
Temp/Rain	4	49.207	12.302	54.4278	<2e-16	0.001
Utilisation	2	0.64	0.32	1.4157	0.2432	
Residuals	980	221.497	0.226			

Growth

	DF	Sum Sq	Mean Sq	F-Value	P-value	Significant at
Stocking Strategy	1	2821	2821	0.014	0.905885	
Temp/Rain	4	3228520	807130	4.0017	3.17E-03	0.01
Utilisation	2	946847	473423	2.3472	0.096176	0.10
Residuals	981	1.98E+08	201699			

TSDM

	DF	Sum Sq	Mean Sq	F-Value	P-Value	Significant at
Stocking Strategy	1	3943182	3943182	37.6142	1.25E-09	0.001
Temp/Rain	4	1609407	402352	3.8381	4.21E-03	0.01
Utilisation	2	74759343	37379672	356.5669	< 2.2e-16	0.001
Residuals	982	1.03E+08	104832			

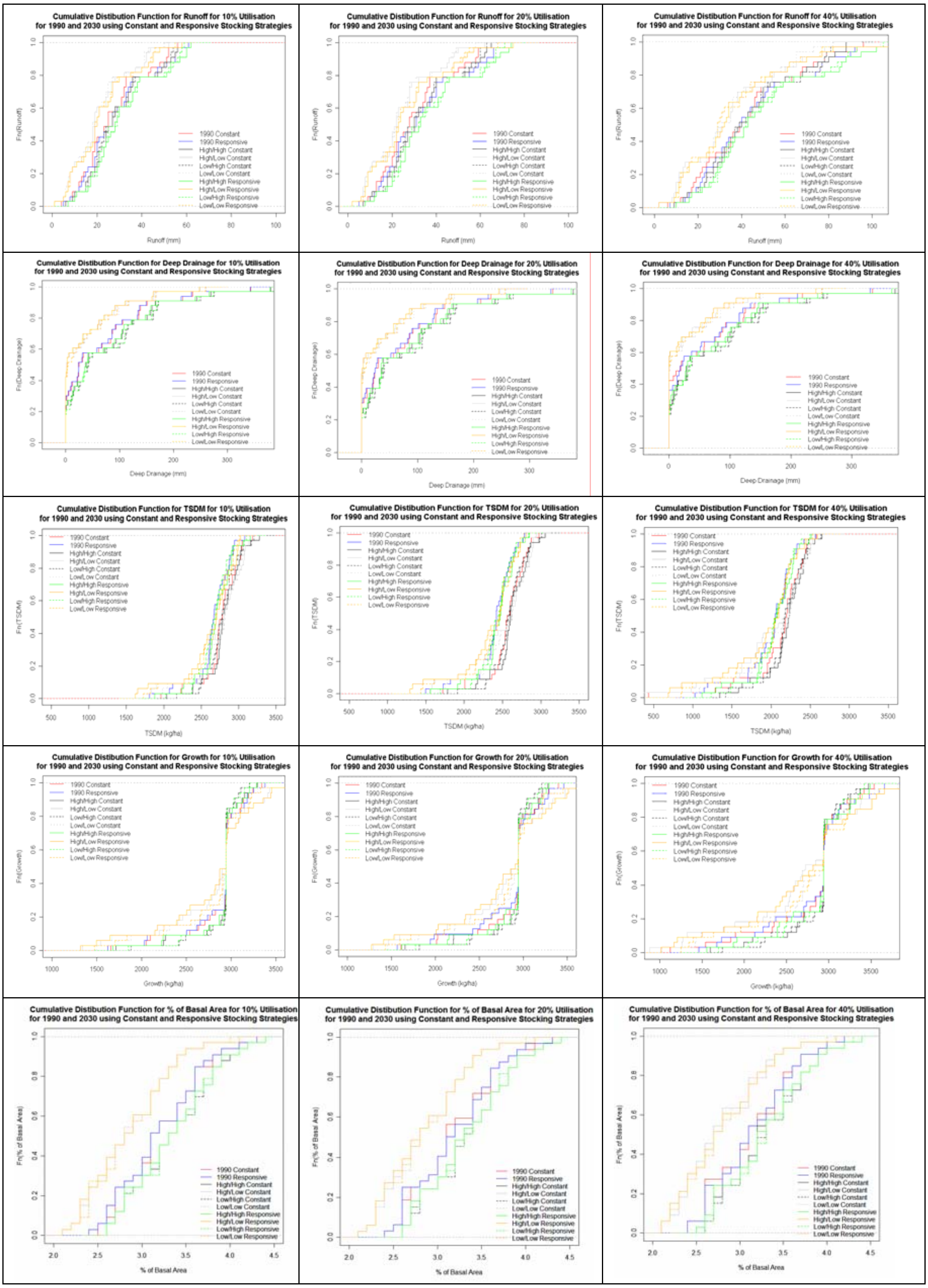
Lwg/hd

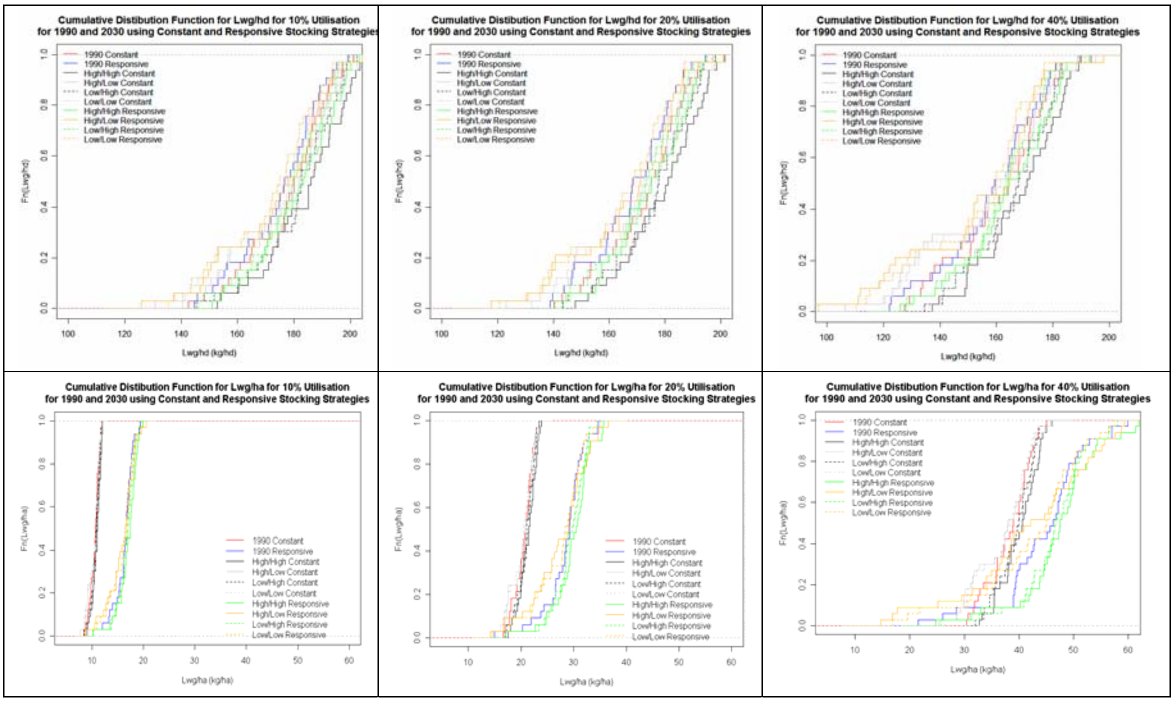
	DF	Sum Sq	Mean Sq	F-Value	P-Value	Significant at
Stocking Strategy	1	3112	3112	10.839	1.03E-03	0.01
Temp/Rain	4	14510	3627	12.635	4.98E-10	0.001
Utilisation	2	52422	26211	91.296	< 2.2e-16	0.001
Residuals	982	281930	287			

Lwg/ha

	DF	Sum Sq	Mean Sq	F-Value	P-Value	Significant at
Stocking Strategy	1	10487	10487	483.2122	< 2.2e-16	0.001
Temp/Rain	4	790	197	9.0988	3.24E-07	0.001
Utilisation	2	130431	65215	3004.814	< 2.2e-16	0.001
Stocking Strategy : Temp/Rain	4	92	23	1.0638	0.373192	
Stocking Strategy : Utilisation	2	213	107	4.9145	0.007525	0.01
Temp/Rain : Utilisation	8	347	43	1.998	0.043812	0.05
Residuals	960	20835	22			

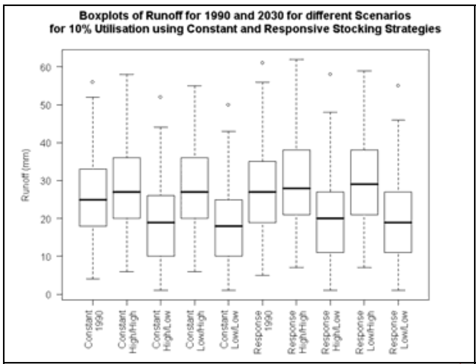
Appendix 5. Cumulative distribution functions of different variables for 10%, 20% and 40 % utilisation

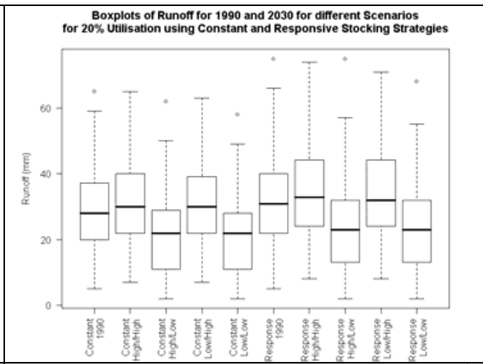


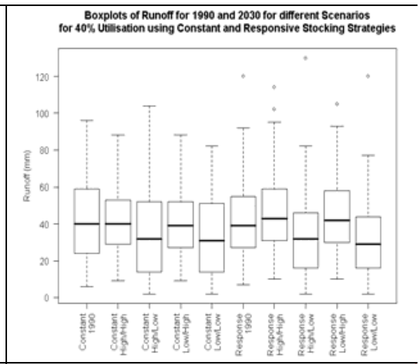


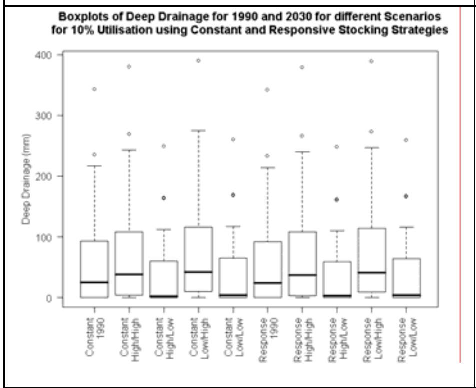
Cumulative Distibution Function for Lwg/hd for 10% Utilisation
for 1990 and 2030 using Constant and Responsive Stocking Strategies
Cumulative Distibution Function for Lwg/hd for 20% Utilisation
for 1990 and 2030 using Constant and Responsive Stocking Strategies
Cumulative Distibution Function for Lwg/hd for 40% Utilisation
for 1990 and 2030 using Constant and Responsive Stocking Strategies
Cumulative Distibution Function for Lwg/ha for 10% Utilisation
for 1990 and 2030 using Constant and Responsive Stocking Strategies
Cumulative Distibution Function for Lwg/ha for 20% Utilisation
for 1990 and 2030 using Constant and Responsive Stocking Strategies
Cumulative Distibution Function for Lwg/ha for 40% Utilisation
for 1990 and 2030 using Constant and Responsive Stocking Strategies
1990 Constant
1990 Responsive
High/High Constant
High/Low Constant
Low/High Constant
Low/Low Constant
High/High Responsive
High/Low Responsive
Low/High Responsive
Low/Low Responsive
Fn(Lwg/hd)
Lwg/hd (kg/hd)
Fn(Lwg/ha)
Lwg/ha (kg/ha)

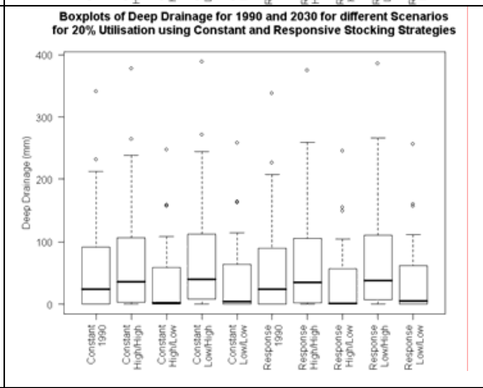
Appendix 6. Box plots of different variables for 10%, 20% and 40% utilisation

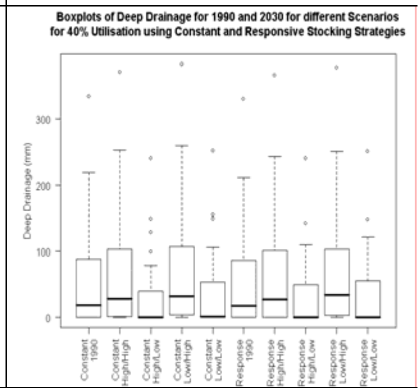


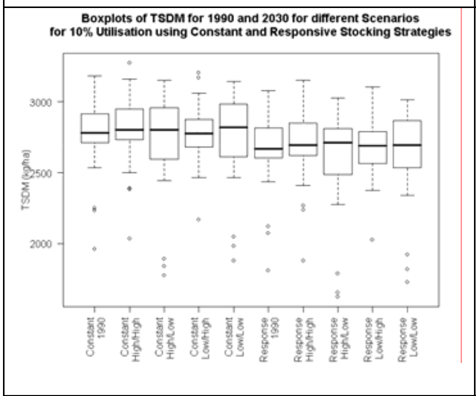


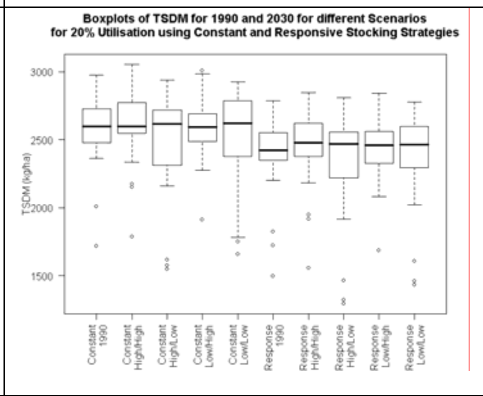


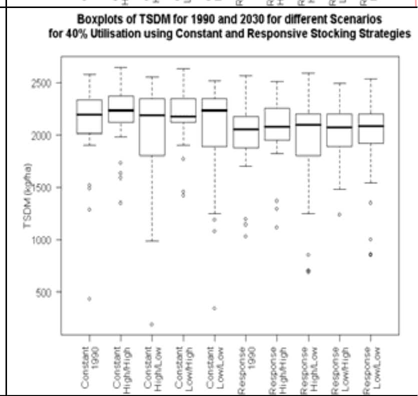


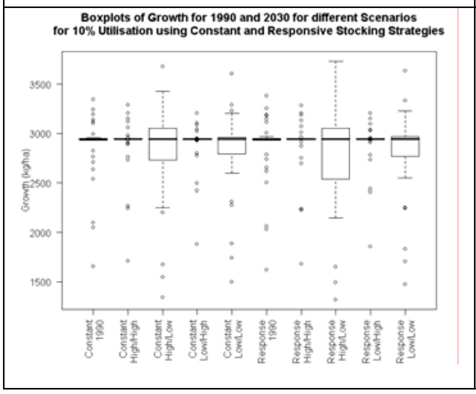


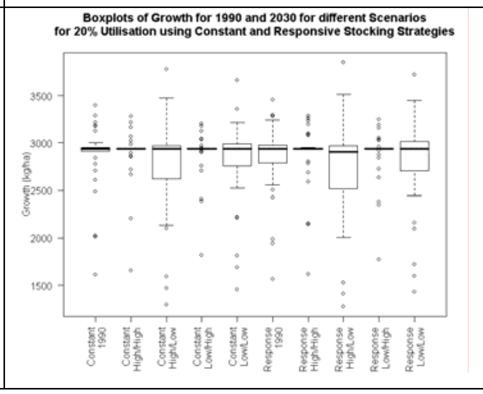


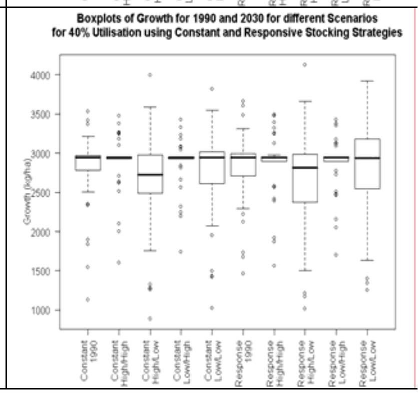


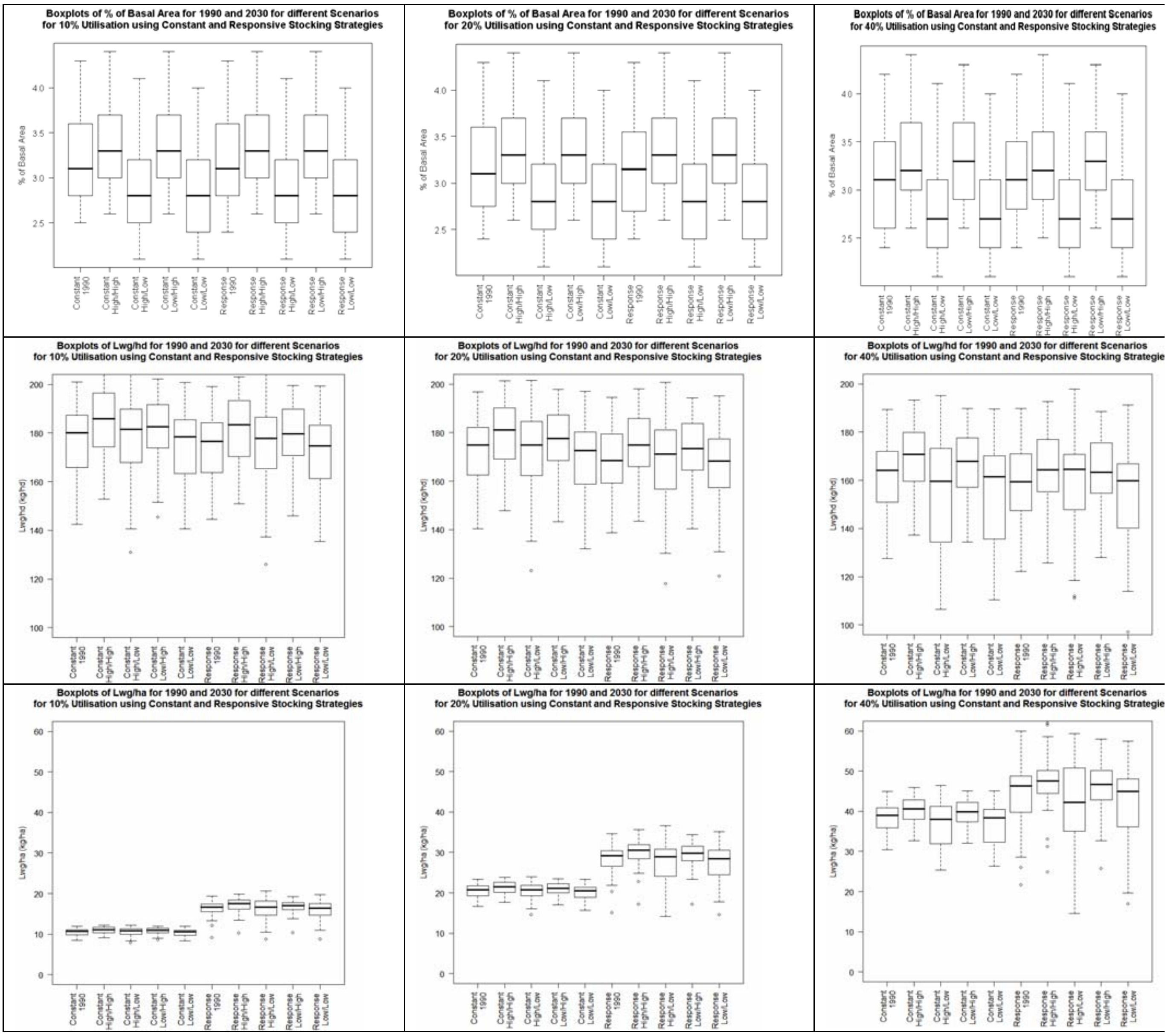




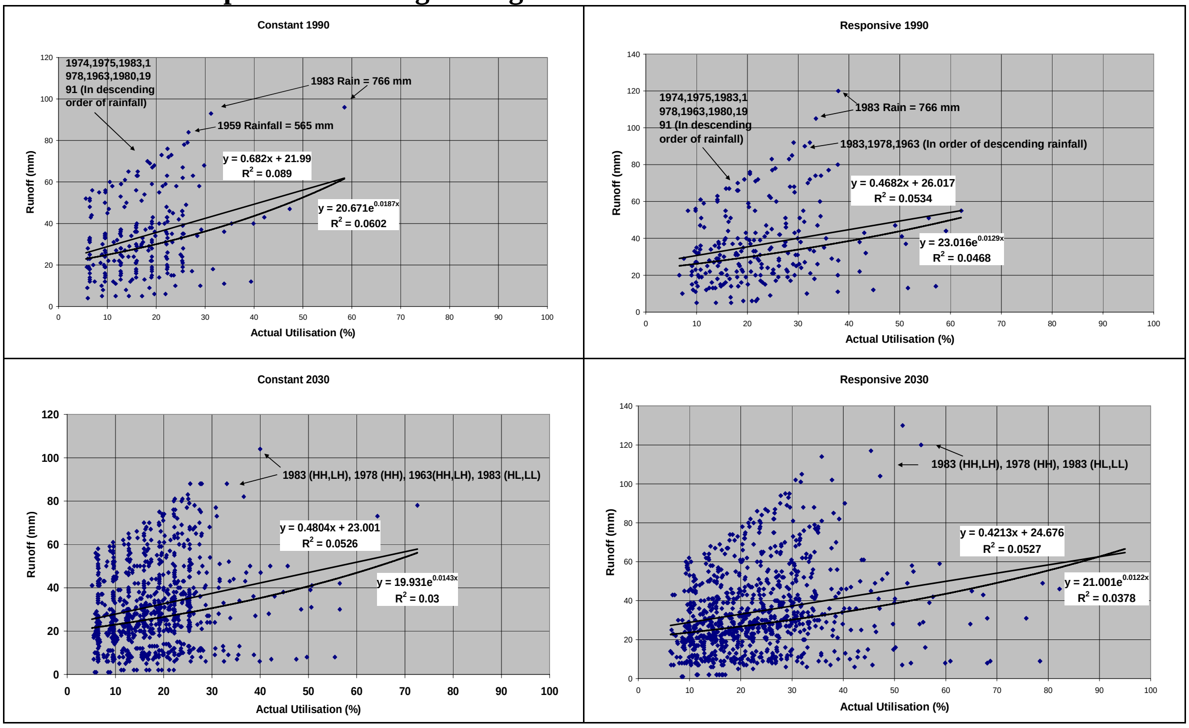




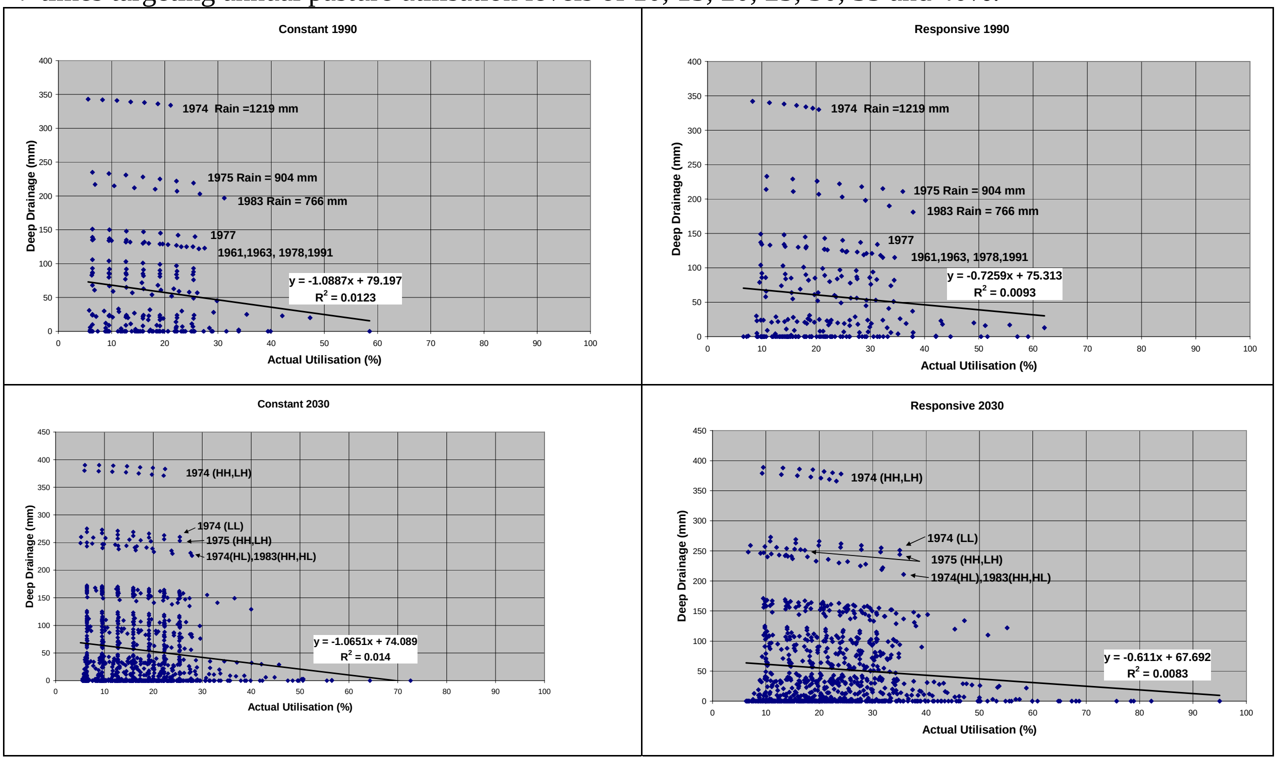



Boxplots of % of Basal Area for 1990 and 2030 for different Scenarios for 10% Utilisation using Constant and Responsive Stocking Strategies
% of Basal Area
Boxplots of % of Basal Area for 1990 and 2030 for different Scenarios for 20% Utilisation using Constant and Responsive Stocking Strategies
% of Basal Area
Boxplots of % of Basal Area for 1990 and 2030 for different Scenarios for 40% Utilisation using Constant and Responsive Stocking Strategies
% of Basal Area
Boxplots of Lwg/hd for 1990 and 2030 for different Scenarios for 10% Utilisation using Constant and Responsive Stocking Strategies
Lwg/hd (kg/hd)
Boxplots of Lwg/hd for 1990 and 2030 for different Scenarios for 20% Utilisation using Constant and Responsive Stocking Strategies
Lwg/hd (kg/hd)
Boxplots of Lwg/hd for 1990 and 2030 for different Scenarios for 40% Utilisation using Constant and Responsive Stocking Strategie
Lwg/hd (kg/hd)
Boxplots of Lwg/ha for 1990 and 2030 for different Scenarios for 10% Utilisation using Constant and Responsive Stocking Strategies
Lwg/ha (kg/ha)
Boxplots of Lwg/ha for 1990 and 2030 for different Scenarios for 20% Utilisation using Constant and Responsive Stocking Strategies
Lwg/ha (kg/ha)
Boxplots of Lwg/ha for 1990 and 2030 for different Scenarios for 40% Utilisation using Constant and Responsive Stocking Strategie
Lwg/ha (kg/ha)

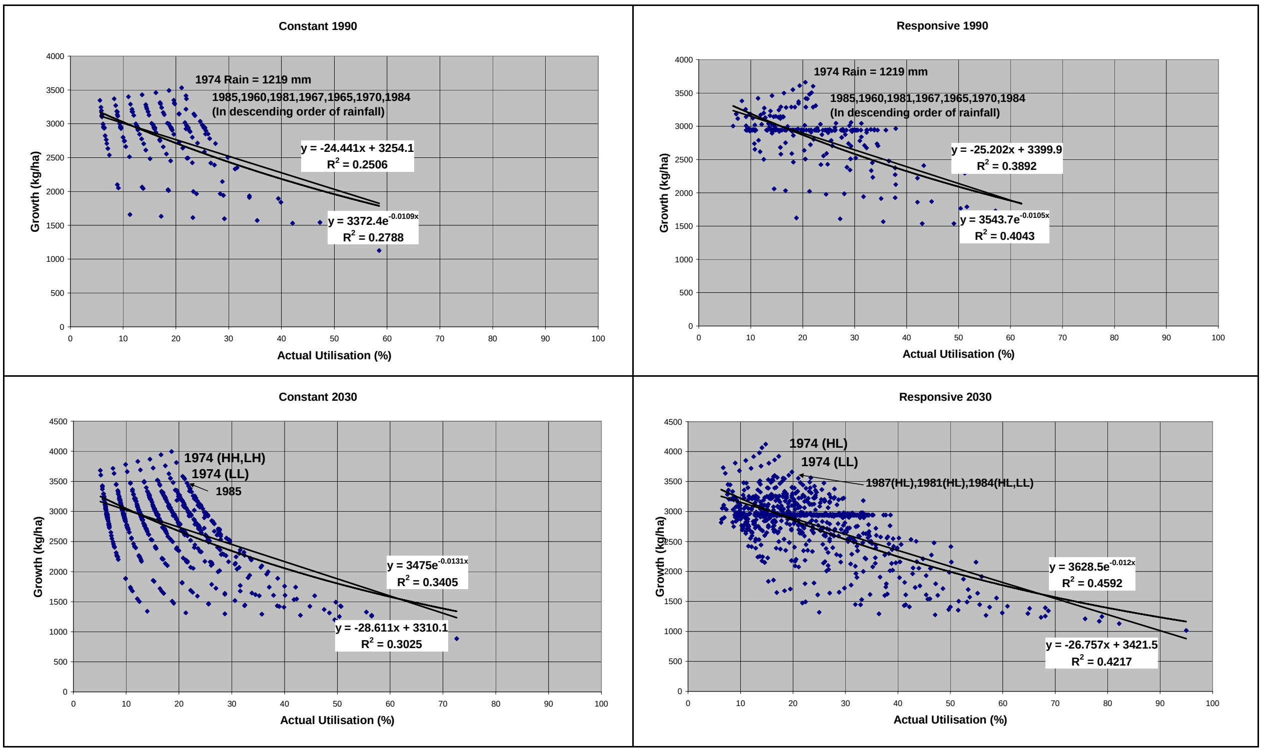
Appendix 7. Scatter plots of different variables against actual utilisation for constant and responsive stocking strategies in 1990 and 2030



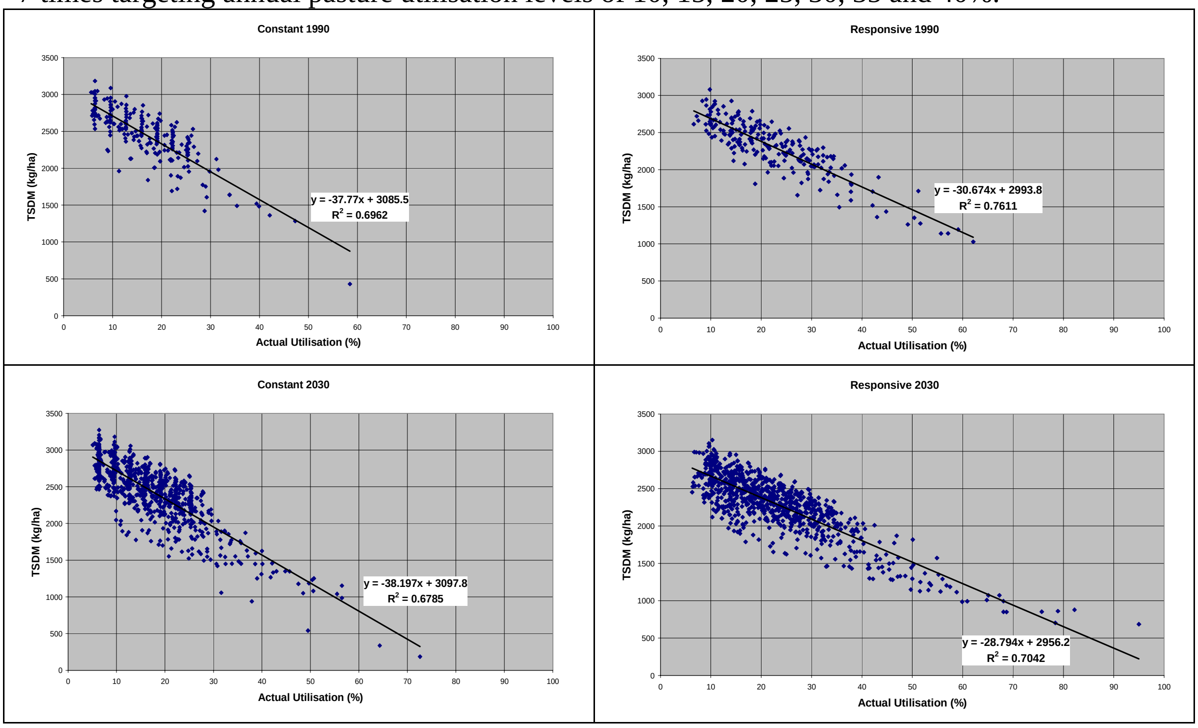
Appendix 7a. Runoff versus actual utilisation for constant (left) and responsive (right) stocking strategies in 1990 (top) and 2030 (bottom) for four climate change scenarios (hh,hl,lh,ll) (n(1990) = 231; n(2030) = 924). These data were generated by running the model 7 times targeting annual pasture utilisation levels of 10, 15, 20, 25, 30, 35 and 40%.



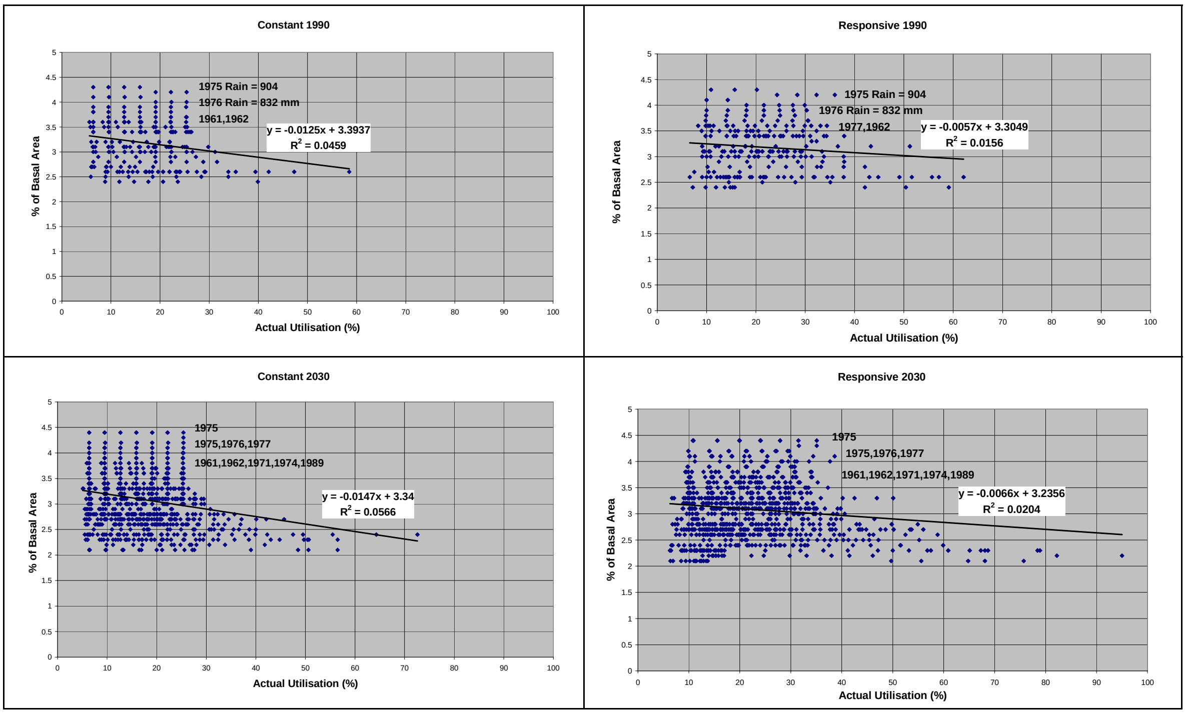
Appendix 7b. Deep drainage versus actual utilisation for constant (left) and responsive (right) stocking strategies in 1990 (top) and 2030 (bottom) for four climate change scenarios (hh,hl,lh,ll) (n(1990) = 231; n(2030) = 924). These data were generated by running the model 7 times targeting annual pasture utilisation levels of 10, 15, 20, 25, 30, 35 and 40%.



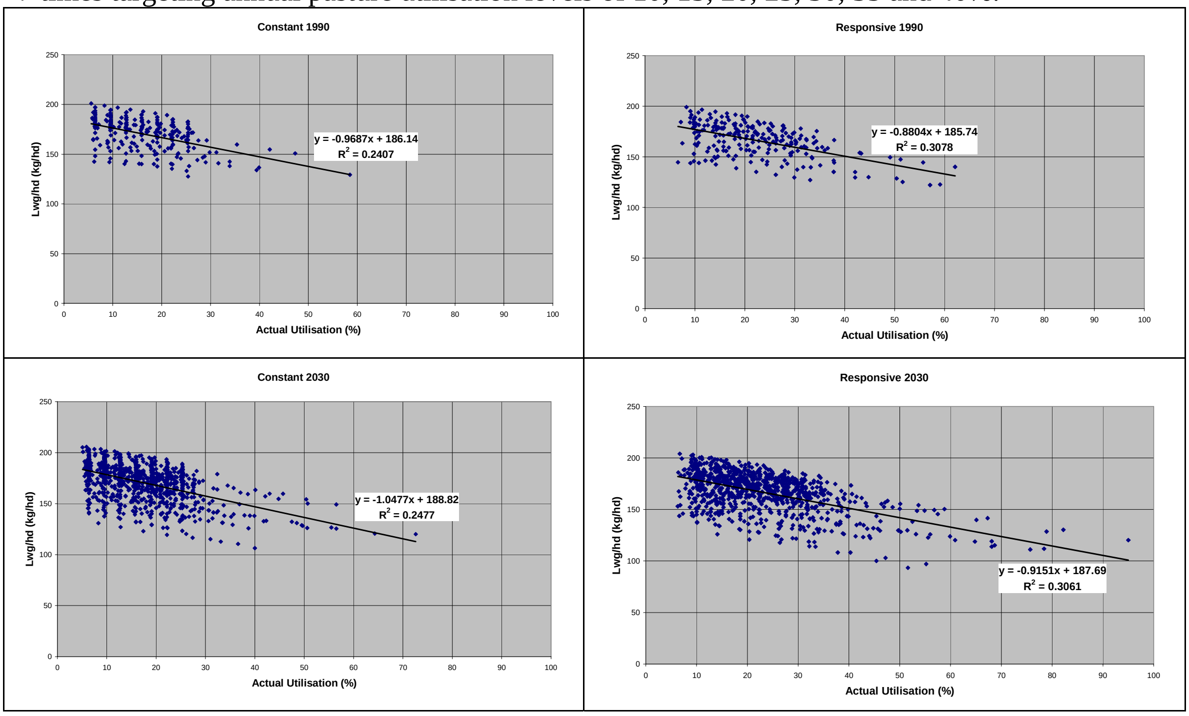
Appendix 7c. Growth versus actual utilisation for constant (left) and responsive (right) stocking strategies in 1990 (top) and 2030 (bottom) for four climate change scenarios (hh,hl,lh,ll) (n(1990) = 231; n(2030) = 924). These data were generated by running the model 7 times targeting annual pasture utilisation levels of 10, 15, 20, 25, 30, 35 and 40%.



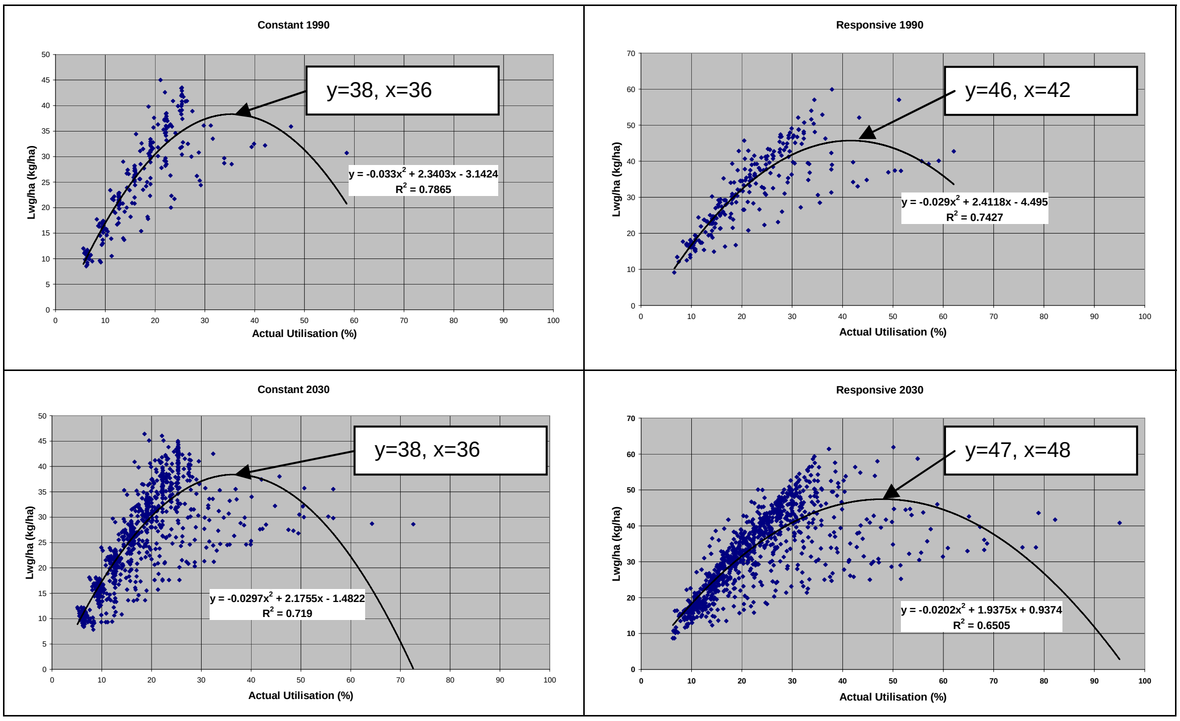
Appendix 7d. Total standing dry matter (TSDM) versus actual utilisation for constant (left) and responsive (right) stocking strategies in 1990 (top) and 2030 (bottom) for four climate change scenarios (hh,hl,lh,ll) (n(1990) = 231; n(2030) = 924). These data were generated by running the model 7 times targeting annual pasture utilisation levels of 10, 15, 20, 25, 30, 35 and 40%.



Appendix 7e. Basal area versus actual utilisation for constant (left) and responsive (right) stocking strategies in 1990 (top) and 2030 (bottom) for four climate change scenarios (hh,hl,lh,ll) (n(1990) = 231; n(2030) = 924). These data were generated by running the model 7 times targeting annual pasture utilisation levels of 10, 15, 20, 25, 30, 35 and 40%.

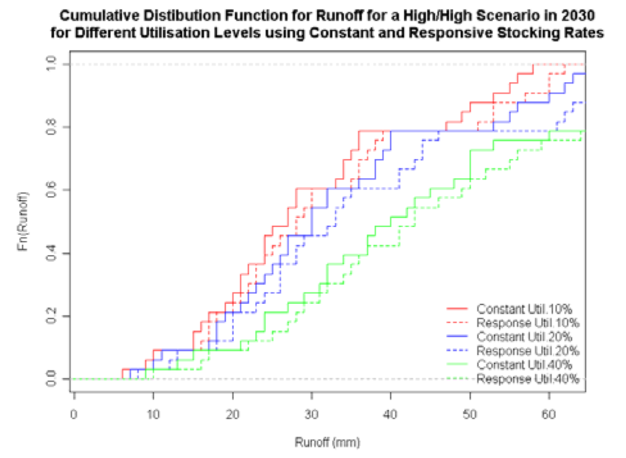


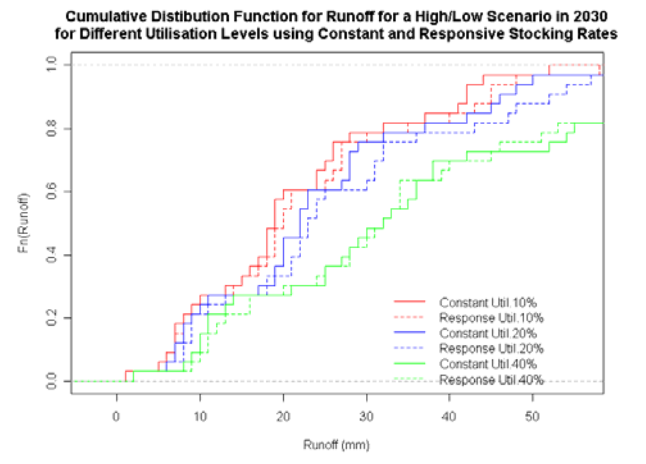
Appendix 7f. Live weight gain per head versus actual utilisation for constant (left) and responsive (right) stocking strategies in 1990 (top) and 2030 (bottom) for four climate change scenarios (hh,hl,lh,ll) (n(1990) = 231; n(2030) = 924). These data were generated by running the model 7 times targeting annual pasture utilisation levels of 10, 15, 20, 25, 30, 35 and 40%.

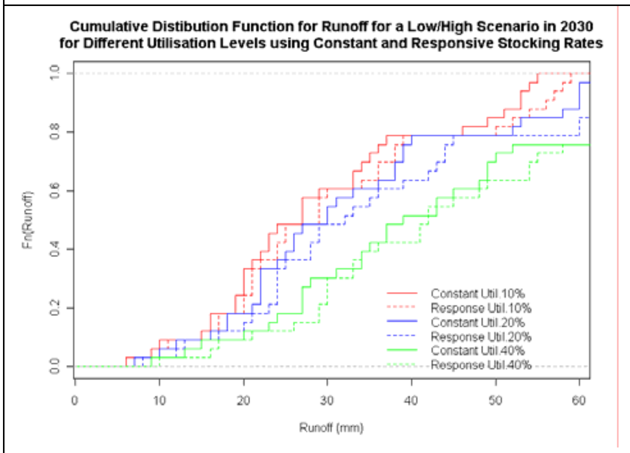


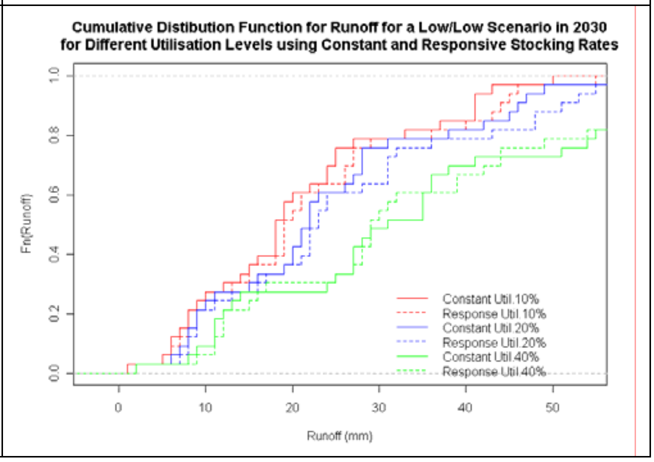
Appendix 7g. Live weight gain per hectare versus actual utilisation for constant (left) and responsive (right) stocking strategies in 1990 (top) and 2030 (bottom) for four climate change scenarios (hh,hl,lh,ll) (n(1990) = 231; n(2030) = 924). These data were generated by running the model 7 times targeting annual pasture utilisation levels of 10, 15, 20, 25, 30, 35 and 40%.

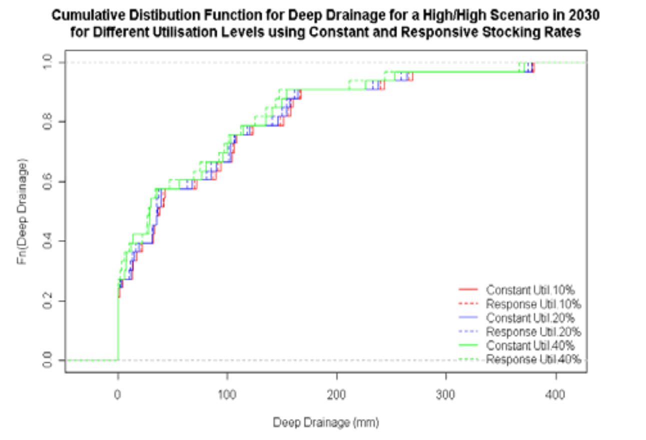
Appendix 8. Cumulative distribution functions of different variables for HH, HL, LH and LL climate change scenarios

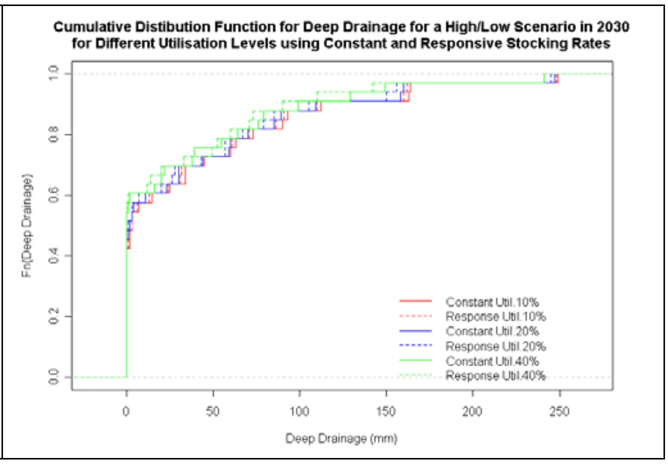


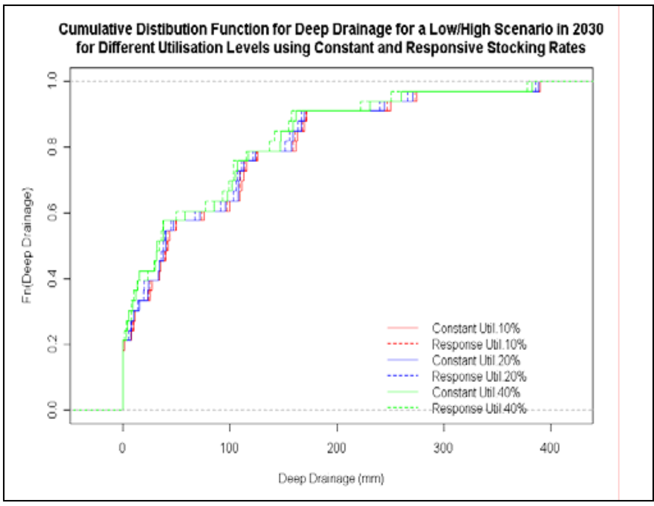


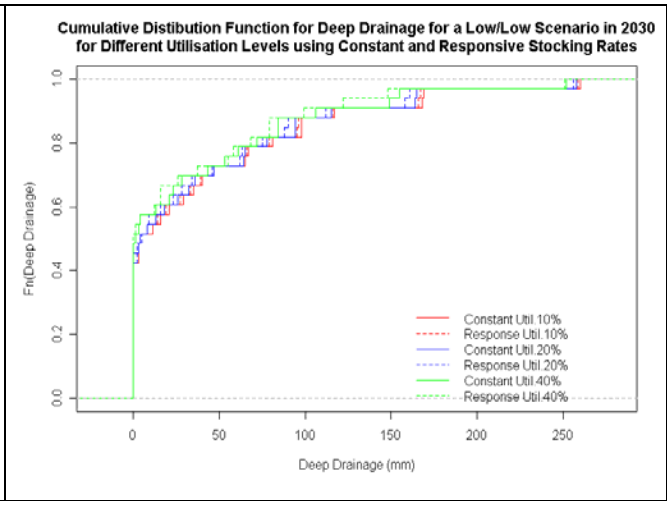


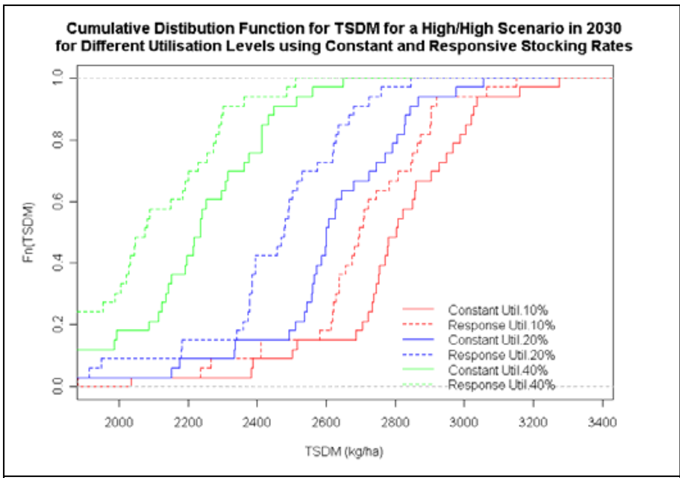


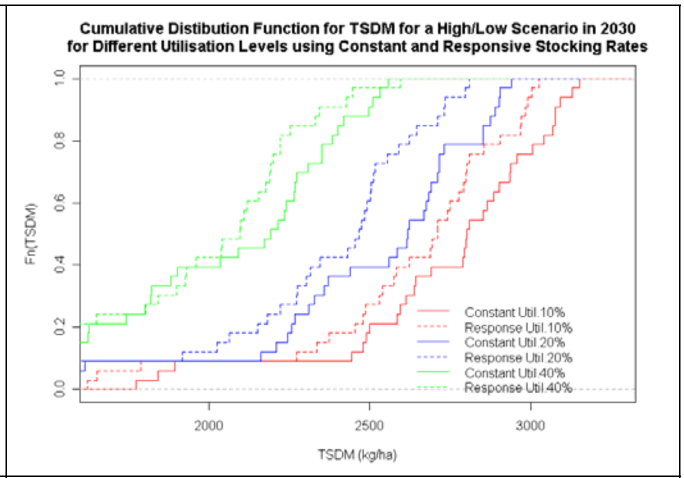


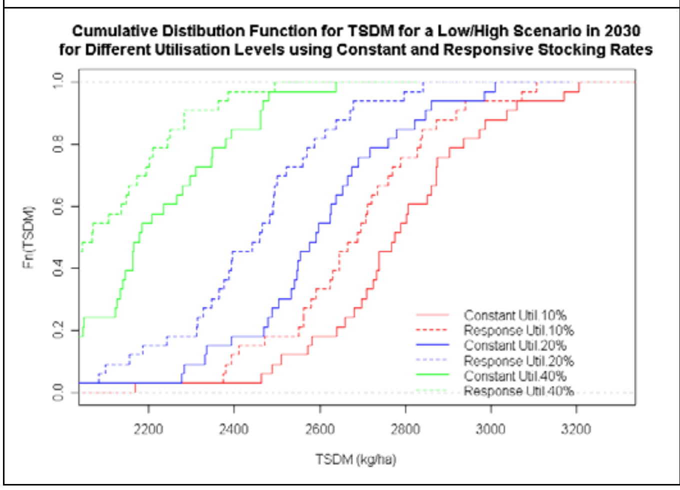


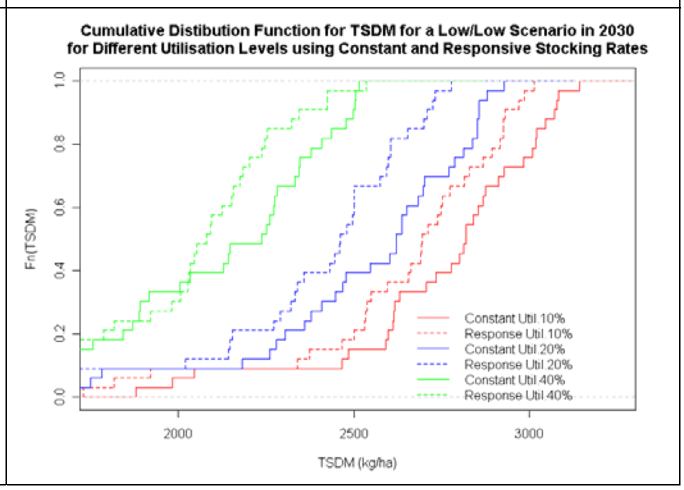

Cumulative Distibution Function for Deep Drainage for a Low/High Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Fn(Deep Drainage)
Deep Drainage (mm)
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%

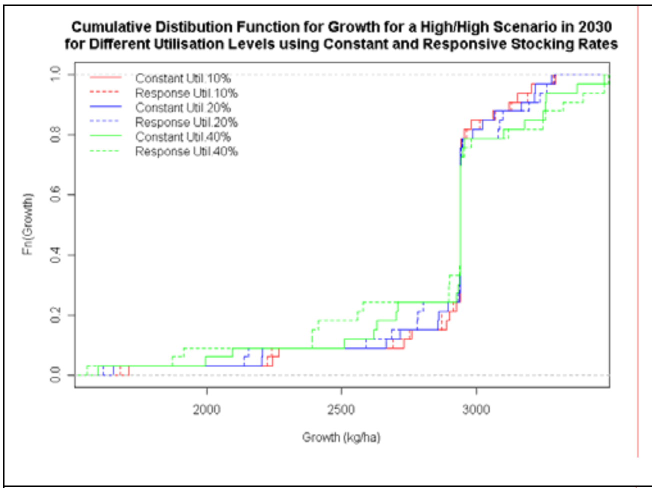

Cumulative Distibution Function for Deep Drainage for a Low/Low Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Fn(Deep Drainage)
Deep Drainage (mm)
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%

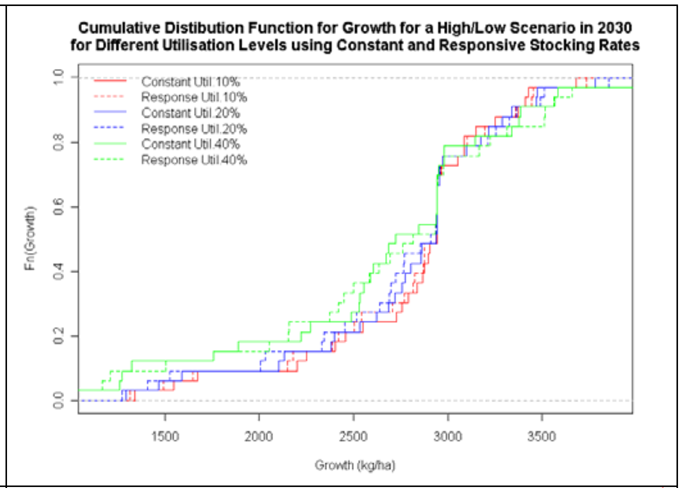

Cumulative Distibution Function for TSDM for a High/High Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Fn(TSDM)
TSDM (kg/ha)
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%

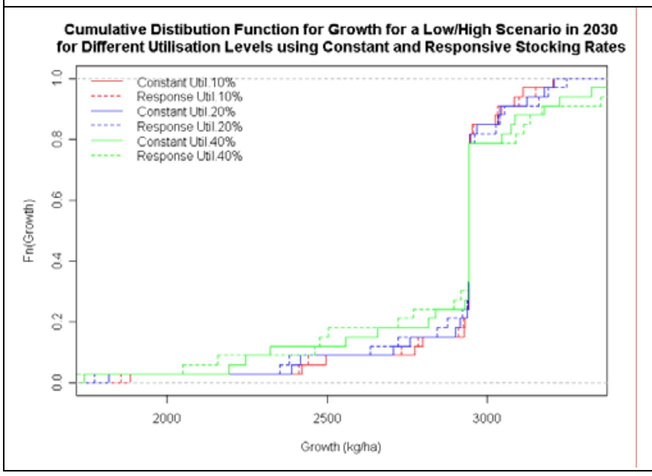

Cumulative Distibution Function for TSDM for a High/Low Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Fn(TSDM)
TSDM (kg/ha)
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%

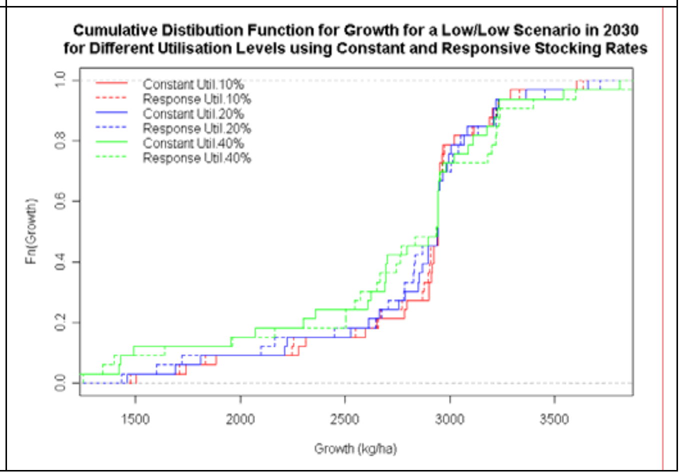

Cumulative Distibution Function for TSDM for a Low/High Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Fn(TSDM)
TSDM (kg/ha)
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%

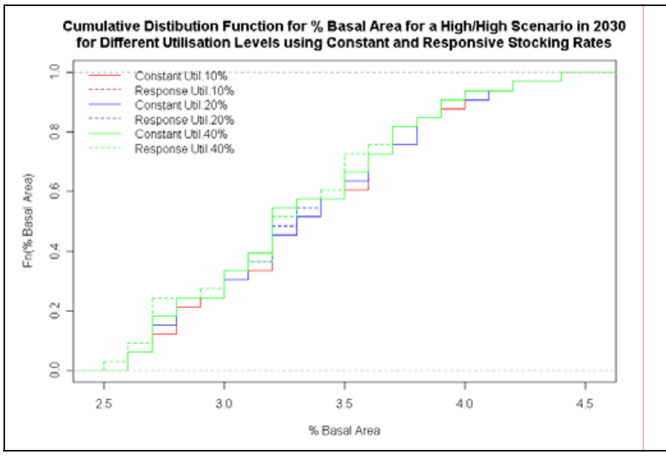

Cumulative Distibution Function for TSDM for a Low/Low Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Fn(TSDM)
TSDM (kg/ha)
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%

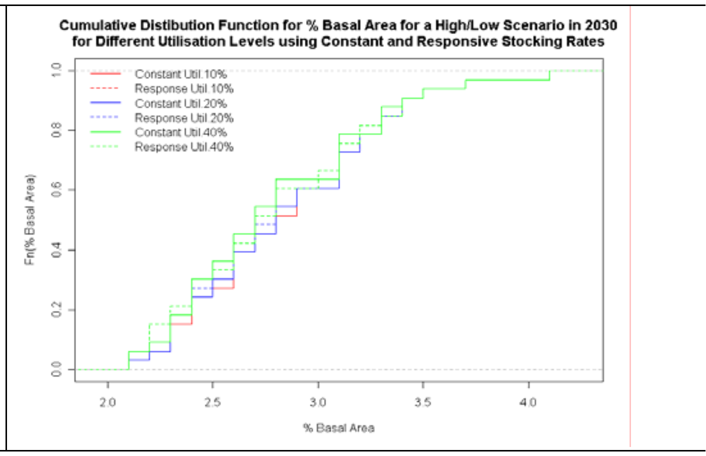

Cumulative Distibution Function for Growth for a High/High Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Fn(Growth)
Growth (kg/ha)

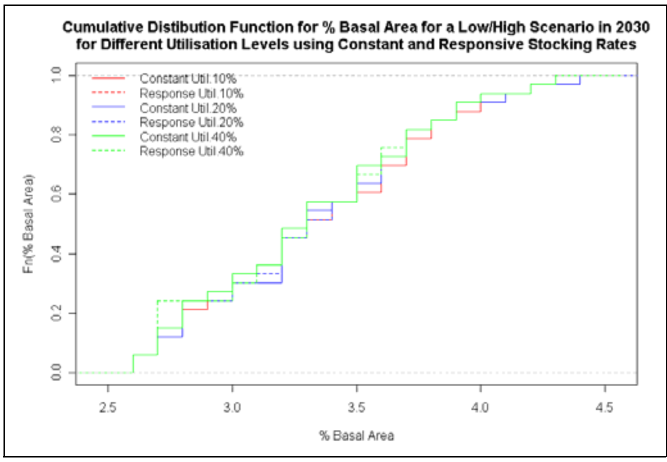

Cumulative Distibution Function for Growth for a High/Low Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Fn(Growth)
Growth (kg/ha)

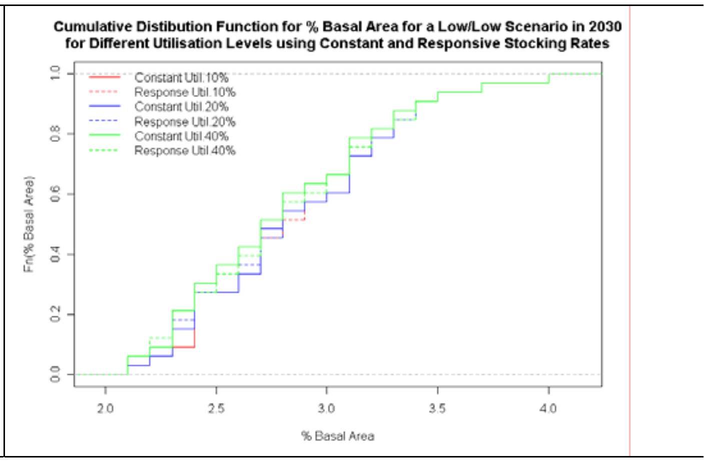

Cumulative Distibution Function for Growth for a Low/High Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Fn(Growth)
Growth (kg/ha)

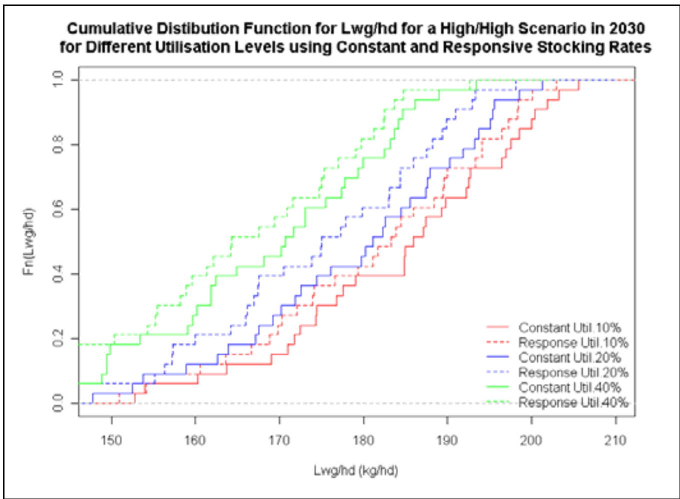

Cumulative Distibution Function for Growth for a Low/Low Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Fn(Growth)
Growth (kg/ha)

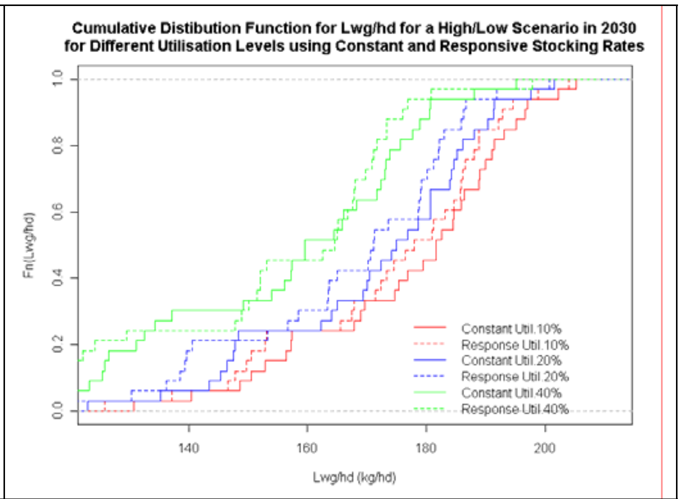

Cumulative Distibution Function for % Basal Area for a High/High Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Fn(% Basal Area)
% Basal Area

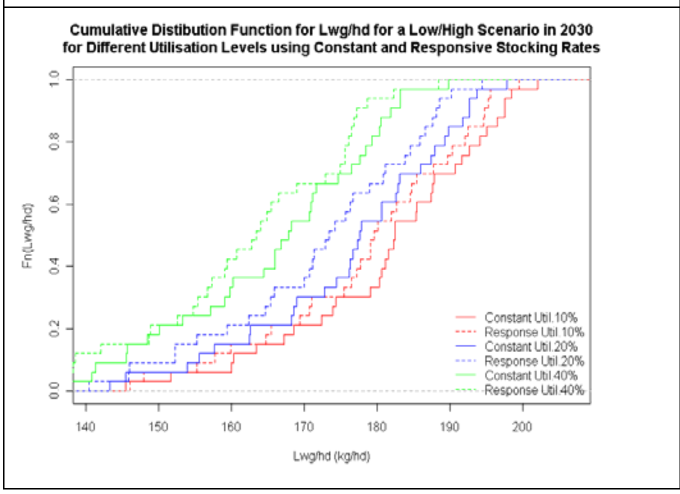

Cumulative Distibution Function for % Basal Area for a High/Low Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Fn(% Basal Area)
% Basal Area

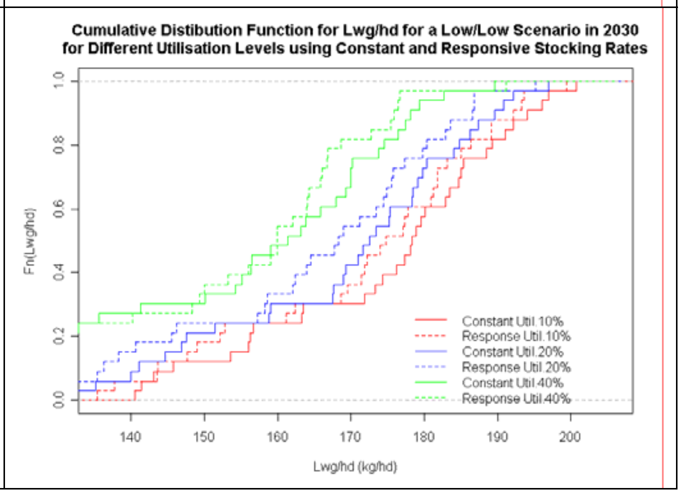

Cumulative Distibution Function for % Basal Area for a Low/High Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Fn(% Basal Area)
% Basal Area

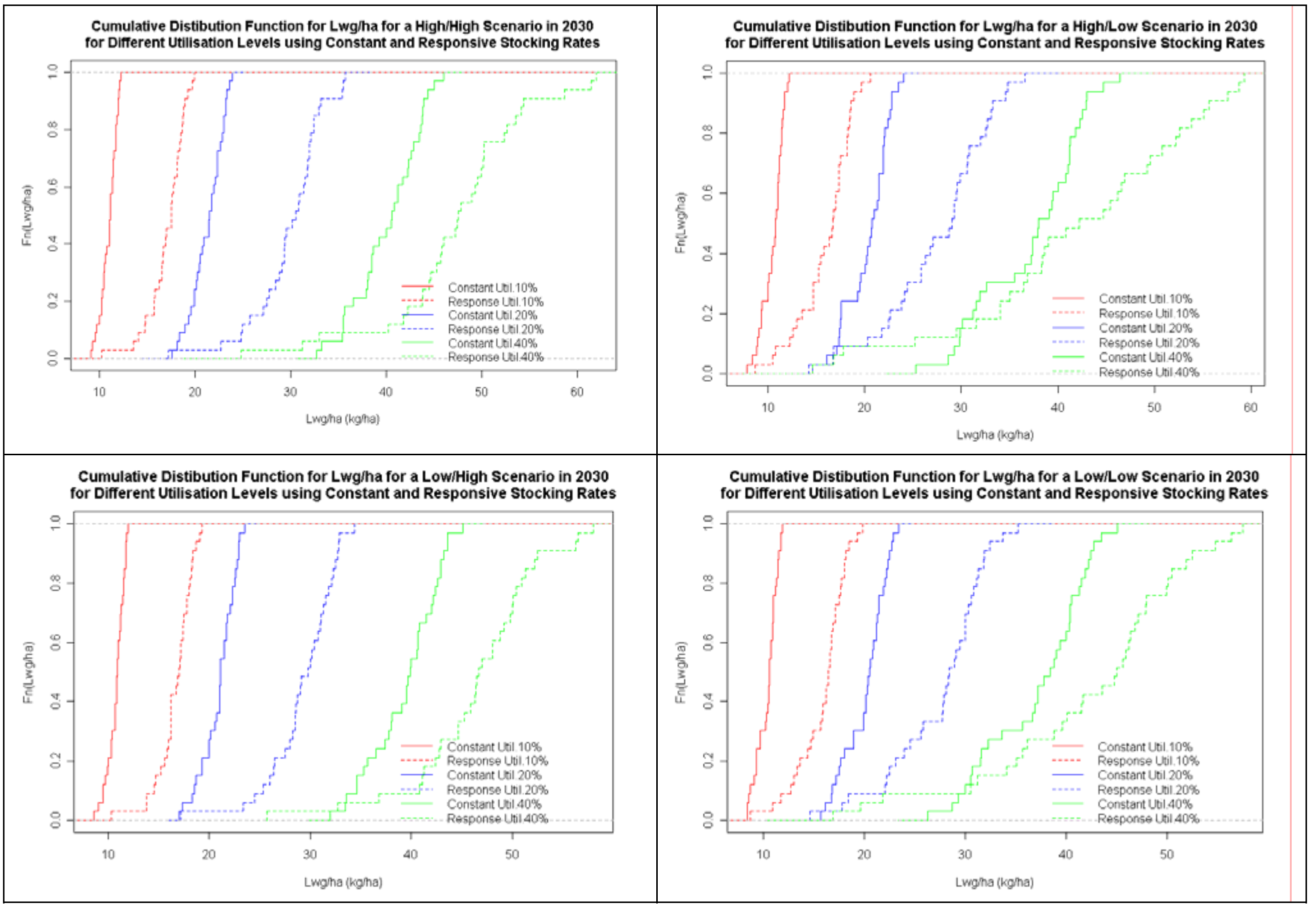

Cumulative Distibution Function for % Basal Area for a Low/Low Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Fn(% Basal Area)
% Basal Area


Cumulative Distibution Function for Lwg/hd for a High/High Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Fn(Lwg/hd)
Lwg/hd (kg/hd)


Cumulative Distibution Function for Lwg/hd for a High/Low Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Fn(Lwg/hd)
Lwg/hd (kg/hd)


Cumulative Distibution Function for Lwg/hd for a Low/High Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Fn(Lwg/hd)
Lwg/hd (kg/hd)


Cumulative Distibution Function for Lwg/hd for a Low/Low Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Fn(Lwg/hd)
Lwg/hd (kg/hd)



Cumulative Distibution Function for Lwg/ha for a High/High Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Fn(Lwg/ha)
Lwg/ha (kg/ha)
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Cumulative Distibution Function for Lwg/ha for a High/Low Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Fn(Lwg/ha)
Lwg/ha (kg/ha)
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Cumulative Distibution Function for Lwg/ha for a Low/High Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Fn(Lwg/ha)
Lwg/ha (kg/ha)
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%
Cumulative Distibution Function for Lwg/ha for a Low/Low Scenario in 2030
for Different Utilisation Levels using Constant and Responsive Stocking Rates
Fn(Lwg/ha)
Lwg/ha (kg/ha)
Constant Util.10%
Response Util.10%
Constant Util.20%
Response Util.20%
Constant Util.40%
Response Util.40%