Final report

NEXUS project: exploring profitable, sustainable livestock businesses in an increasingly variable climate

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Abstract

Changing climates, and increased pressure from government and consumers to reduce the impacts of red meat on the environment threaten the viability of red meat production in Australia. We used bioeconomic modelling of a constructed case study farm in the Northern Downs region of Queensland to understand the impacts of a future climate (centred on 2050) on the productivity, profitability, and sustainability of beef production, and to evaluate a range of interventions. We also used semi-structured interviews to understand human adaptive and transformation capacity. Without changes to management, productivity, profitability, and sustainability of beef production in the Northern Downs region is predicted to decrease by 2050. Of the activities modelled, improving the feedbase through oversowing of herbaceous legumes, and transitioning from a breeder herd to steer turnover operation resulted in the greatest improvements in productivity and profitability. Large decreases in methane emissions, on a per ha and per kg liveweight sold basis, were possible through changing to a steer turnover operation and through the application of novel technologies that could provide reductions in the production of enteric methane. The results provide an indication of potential adaptation pathways for the industry and highlight gaps for future research and development.

Executive summary

Background

Climate is a key risk to the future profit of Australian red meat grazing systems. Changes in the climate of eastern Australia have already occurred over the past two decades, including increasing temperatures and heat waves, declining rainfall in south-eastern Australia and increased severity of extreme events. Livestock businesses need to adapt to the changes that have already occurred and prepare for the anticipated climate changes over the next decade, including further increases to temperature and a greater frequency of extreme climate events such as heat waves and extreme rainfall. At the same time, producers are also under pressure from consumers and regulators to decrease their impacts on the environment.

In response to these challenges, the NEXUS project is a multi-party program that explores the nexus between profitability, productivity, greenhouse gas mitigation and carbon sequestration in an increasingly variable climate. An integrated assessment of seven farm case studies across eastern Australia was used to identify systems adaptations that are both profitable and sustainable. This report focuses on the North Queensland case study in the Northern Downs region.

Objectives

Objective 1. Model the impact of climate change scenarios against two future time horizons (2030 and 2050) on a beef production system in Northern Queensland using a method consistent with the other NEXUS projects and sites.

The Northern Queensland case study was modelled under four future climate projections for 2050. The main trend for future climate in this region is continued high year-to-year variability, with little change in average conditions between 2030 and 2050.

Objective 2. Identify 10 prospective high priority research themes each for the beef and feedbase areas that mitigate the long-term impact of a changing climate. These themes will then be refined through engagement with the regional reference group to identify the most prospective areas for further investigation.

Research priorities were identified in consultation with the regional reference group.

Objective 3. Engage a minimum of 10 producers in strategic activities to explore the profitability and resilience of their production system against future climate change scenarios.

The project interacted with a number of producers, QDAF extension officers and staff from Southern Gulf NRM through the regional reference group, informal property visits, and interviews to explore adaptive capacity.

Objective 4. Calculate greenhouse gas emissions on the case study farm and investigate prospective abatement or mitigation methods, followed by modelling of the impacts of these strategies on total emissions.

The main source of greenhouse gas emissions from the case study enterprise is enteric methane from grazing cattle. Activities to reduce enteric methane were included in the bioeconomic modelling. Methods to sequester carbon in the landscape were not considered feasible for this case study, and were not included in the modelling component.

Objective 5. Conduct a skills assessment to determine what skills, capacities and capabilities will be required to equip the industry to adapt to modelled climate change scenarios and develop recommendations for pathways to develop these required skills, capacities, and capabilities.

Interviews were conducted with a diverse range of producers to understand their adaptive capacity in the context of scenarios explored in the bioeconomic modelling component of the project.

Methodology

The project used bioeconomic modelling of a constructed case study farm to understand the impacts of a future climate on productivity, profitability, and greenhouse gas emissions, and to evaluate a range of interventions. The baseline scenario consisted of a 40-year run centred on the year 2000 (1980-2019), and the future climate centred on 2050. The baseline model and future management scenarios were developed in consultation with a regional reference group and informed by other NEXUS case studies. The project also used semi-structured interviews with producers, some of whom were members of the reference group, to understand human adaptive and transformation capacity.

Results/key findings

Without changes to management, the productivity, profitability, and sustainability of beef production in the Northern Downs region is predicted to decrease by 2050. Of the activities modelled, improving the feedbase through oversowing of herbaceous legumes, and transitioning from a breeder herd to steer turnover operation resulted in the greatest improvements in productivity and profitability. Large decreases in methane emissions, on a per ha and per kg liveweight sold basis, were possible through changing to a steer turnover operation and through the application of novel technologies (like a rumen bolus) that might provide large reductions in the production of enteric methane.

Benefits to industry

The project provides an evaluation of potential activities and technologies that will support the productivity, profitability, and sustainability of beef production in a changing climate.

Future research and recommendations

Based on the bioeconomic modelling, feedback from the regional reference group, and industry interviews, key recommendations for future research and development include:

1) Research into pasture species capable of persisting in a variable climate. This could include novel species, or selective breeding and development of existing endemic species.
2) Focus on identifying and development more locally appropriate technologies to reduce emissions from livestock production, or store carbon in landscapes.
3) Improved understanding of the frequency, intensity and impacts of extreme events like flooding, which are difficult to predict and plan for.
4) Larger scale modelling of climate change impacts on beef production, which account for interactions across the supply chain, especially relating to prices and markets.

Acknowledgements

We would like to thank the producers and industry staff who participated in the regional reference group and interviews for being so generous with their time and sharing their knowledge of the region and local beef production systems. We also thank the other NEXUS case studies for their shared approach to this project.

Acknowledgement is made to the Queensland Government who are the custodians for the GRASP model code and provide ongoing model testing and improvement.

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1. Background

Climate is a key risk to the future profit of Australian red meat grazing systems. Changes in the climate of eastern Australia have already occurred over the past two decades, including increasing
temperatures and heat waves, declining rainfall in south-eastern Australia and increased severity of extreme events (CSIRO and Bureau of Meteorology 2015). Livestock businesses need to adapt to the changes that have already occurred and prepare for the anticipated climate changes over the next decade, including further increases to temperature and a greater frequency of extreme climate events such as heat waves and extreme rainfall. At the same time, producers are also under pressure from consumers and regulators to decrease their impacts on the environment, leading MLA to adopt a red meat industry target of carbon neutrality by 2030.

In response to these challenges, the NEXUS project is a multi-party program that explores the nexus between profitability, productivity, greenhouse gas mitigation and carbon sequestration in an increasingly variable climate. An integrated assessment of seven farm case studies across eastern Australia (Figure 1) was used to identify systems adaptations that are both profitable and sustainable. This report focuses on the North Queensland case study in the Northern Downs region.

Figure 1. Map of NEXUS case study sites

2. Objectives

Objective 1. Model the impact of climate change scenarios against two future time horizons (2030 and 2050) on a beef production system in Northern Queensland using a method consistent with the other NEXUS projects and sites.

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3. Methodology

The project used bioeconomic modelling of a constructed case study farm to understand the impacts of a future climate on productivity, profitability, and greenhouse gas emissions, and to evaluate a range of interventions. The baseline scenario consisted of a 40-year run centred on the year 2000 (1980-2019), and the future climate centred on 2050. Climate projections for the case study region emphasise high variability between years, rather than a strong drying trend like some of the southern case study regions. For this reason, it was decided not to model the 2030 climate. Instead, we explored the variation in possible climate futures for 2050 (via four global climate models), and adaptation options that may support productive, profitable, and sustainable beef enterprises under a highly variable climate.

The baseline model and future management scenarios were developed in consultation with a regional reference group and informed by other NEXUS case studies. The reference group was comprised of producers, Queensland Department of Agriculture and Fisheries (QDAF) extension staff and project officers from Southern Gulf Natural Resource Management (NRM), with representatives from the latter two organisations contributing their own personal and practical experiences to the group as well as a broad overview of the industry gained through their professional roles.

The project also used semi-structured interviews with producers, some of whom were members of the reference group, to understand human adaptive and transformation capacity.

All activities were reviewed and approved by the CSIRO Social and Interdisciplinary Science Human Research Ethics Committee (120/20). Psuedonyms are used in the reporting of results to protect the privacy of individuals.

3.1 North Queensland case study

The case study is situated in the Northern Downs region and builds on a previous case study developed by the Queensland Department of Agriculture and Fisheries as part of the Drought and Climate Adaptation Program (DCAP) (Bowen *et al.* 2020). The case study is a constructed farm, based on extensive review of literature and consultation with local producers and experienced scientific and extension teams. Production parameters were intended to represent the long-term average expectation for the region, noting that there is high variability in average annual rainfall, and therefore productivity, in this area.

The Northern Downs consists mainly of Open and Ashy Downs – open and undulating Mitchell Grass Plains with isolated trees, draining into open alluvial plains, gidgee woodlands, wooded downs, jump ups or soft mulga sand ridges (Queensland Government 2011) (Figure 2). Soils are alkaline, cracking clays with self-mulching surfaces, and generally contain adequate phosphorus for livestock production. The dominant vegetation type are perennial native Mitchell grasses (*Astrebla* spp), characterised by resilience under heavy grazing and variable rainfall. Average land condition in this area is B, though this is threatened by overgrazing and the invasion of woody weeds.

Figure 2. Typical Ashy Downs country, McKinlay Shire, May 2021 [photo: D Mayberry, CSIRO]

The environment of the Northern Downs is characterised as semi-arid to arid, with long dry seasons, extreme temperatures, high evaporation rates and high rainfall variability. To illustrate, historical annual rainfall at Julia Creek Post Office ranges from 106 mm in 1952 to 1,084 mm in 1974 (Figure 3). Average annual rainfall for Julia Creek between 1980-2019 was 461 ± 172 (mean ± standard deviation) mm, with the majority falling between November and March (Figure 4). Effective (>10 mm) out of season winter rainfall (May to October) can promote pasture growth. However, smaller amounts followed by unfavourable (i.e., cold, windy) conditions cause mould and blackening of standing grass, markedly decreasing palatability and feed value. The McKinlay and Richmond Shires, which comprise a large portion of the Northern Downs region, were fully drought-declared by the Queensland Government in April 2013, with this status only recently lifted in June 2023 (Queensland

Government 2023a). They also experienced extreme flooding, followed by a cold weather event, in January 2019, which caused large losses of stock and farm infrastructure (Phelps 2019).

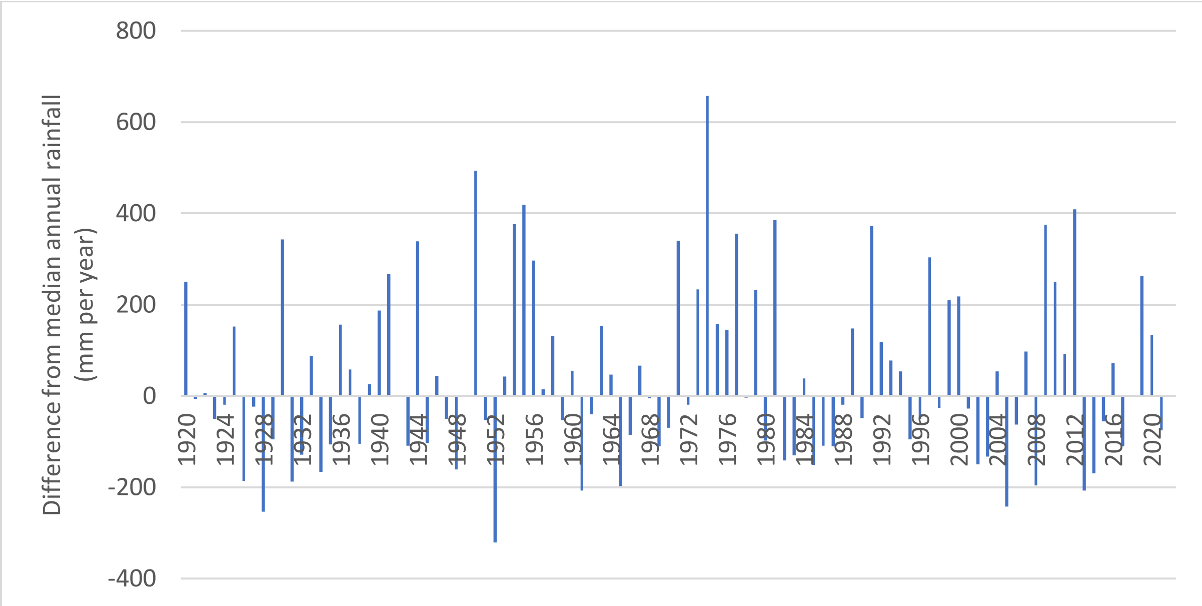

Figure 3. Deviation from median annual rainfall (425 mm) at Julia Creek between 1920 and 2021 (Queensland Government 2023b)

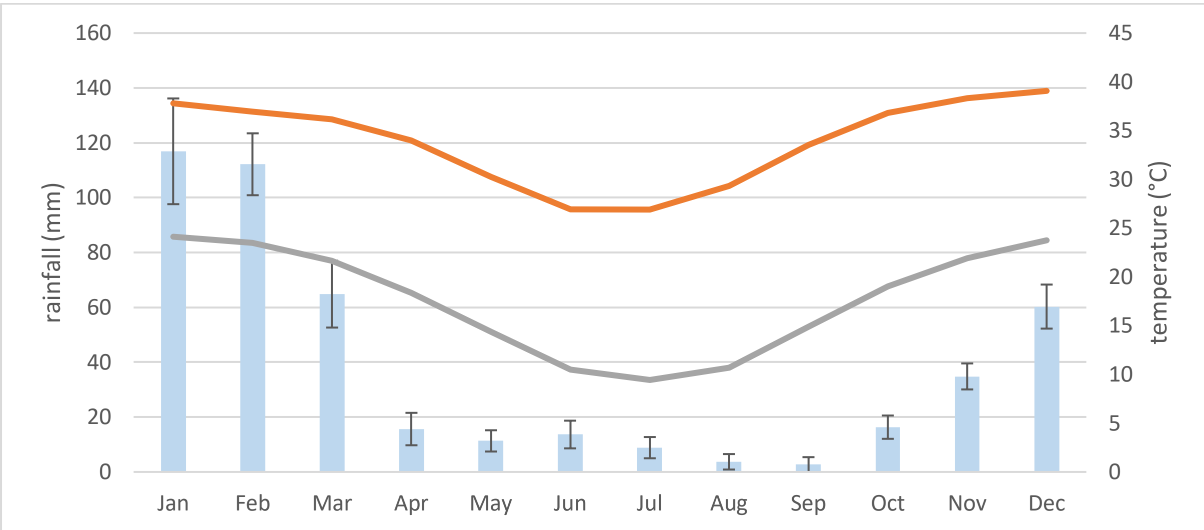

Figure 4. Baseline climate data for Julia Creek, 1980-2019. Blue columns are average monthly rainfall with standard error bars. Lines show average minimum (grey) and maximum (orange) daily temperatures.

3.2 Bioeconomic modelling

Bioeconomic modelling provides an indication of what *could* happen under the scenarios described below. The modelled case study does not represent a specific farm business, but is based on a constructed, hypothetical enterprise which was realistic for the region. It is anticipated that by understanding the assumptions underpinning our model, which are detailed in this section, those reading this report can use their judgement to assess how our results might be relevant to their region or business.

3.2.1 The Crop-Livestock Enterprise Model (CLEM)

The case study enterprise is modelled using the Crop Livestock Enterprise Model (CLEM). While it was desirable for model outputs to be directly comparable between the NEXUS case studies, the models used to simulate southern grazing and mixed crop-livestock systems are not suitable for modelling northern systems, and vice versa, so we advise care in making direct comparisons. Our modelling approach is also different to that used by Bowen *et al.* (2020) and there will be differences in outputs despite similar baseline parameters.

CLEM is an updated version of the North Australian Beef Systems Analyser (NABSA) and sits within the APSIM NextGen framework (Holzworth *et al.* 2018). The NABSA model has been widely tested and validated across northern Australia (Ash *et al.* 2015) but is no longer supported. CLEM runs on a monthly time-step and contains a herd sub-model, with native pasture production simulated in GRASP (Rickert *et al.* 2000) and imported into CLEM. The model outputs animal production data and greenhouse gas emissions from enteric methane fermentation (the major source of emissions in the case study system) but does not simulate changes in carbon stocks or greenhouse gas emissions from other agricultural processes or farm activities. It also includes an economic model that tracks income and expenses over time.

The CLEM herd sub-model is based on equations from the Australian Feeding Standards (Freer *et al.* 2007). These equations simulate feed intake, growth, reproduction, and survival based on the feed available (quantity and quality) and management rules implemented in the model and can be adjusted to reflect the characteristics of different animal genotypes. Enteric methane is calculated using the equation of Charmley *et al.* (2016) based on modelled dry matter intake, which is a function of animal size and feed availability. The main difference between CLEM and other herd models is that it models the performance of individual animals rather than whole cohorts (typically age and sex class). It also allows for the implementation of dynamic herd management rules in response to different conditions, creating variability within a herd. So, for example, while some models may assume that all cows are joined in a single month, CLEM allows for controlled mating over a specified period (in this case January – May), with an equivalent spread in calf birth dates, and therefore variations in growth rates in response to age and feedbase interactions.

The GRASP model inputs include detailed climate data (minimum and maximum temperatures, rainfall, evaporation, radiation, vapour pressure), which determines the amount of biomass produced (Figure 5). Pasture quality is defined with CLEM, with users specifying N content and digestibility of new growth, and degradation of existing biomass each month. Feedbase is the primary driver of productivity, and profitability is heavily influenced by the sequence of good and bad years. To account for this, a ‘rainfall shuffler’ tool is deployed within CLEM to randomise the sequence of years for pasture inputs within a 40-year model run. This means that each run produces different results, and the results reported for this case study are the average of five 40-year model runs.

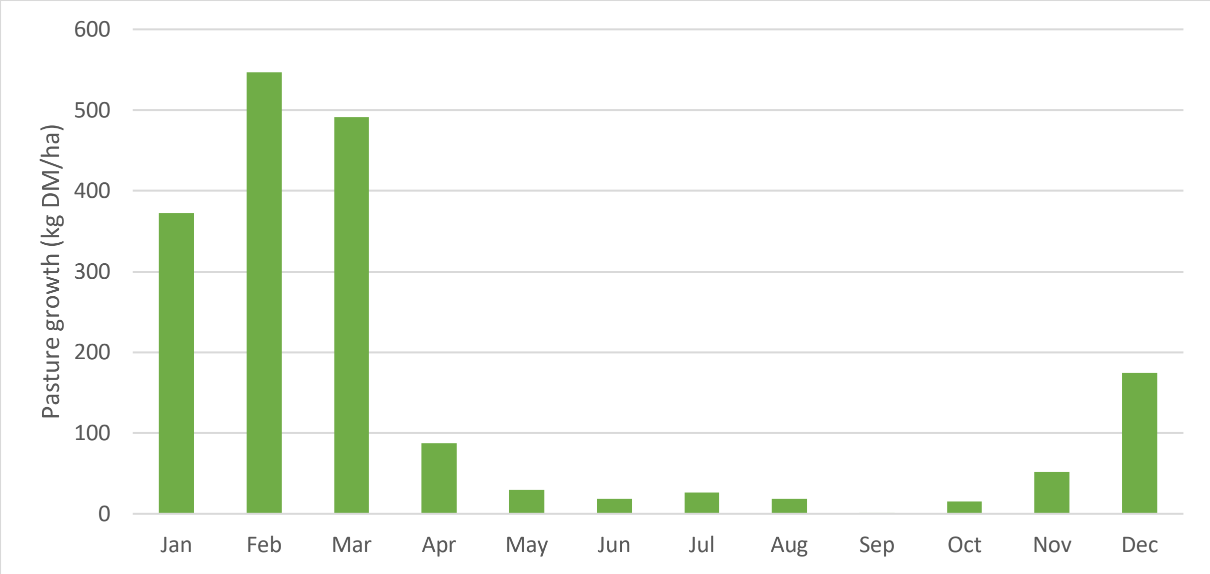

Figure 5. Average monthly pasture biomass growth 1980-2019 modelled using GRASP

Financial performance of scenarios was assessed using Gross Margins (GM; gross revenue from animal sales minus variable costs) and earnings before interest, taxes, depreciation, and amortisation (EBITDA; total revenue minus variable and overhead costs). Both are reported on a financial year basis, with 39 full financial years over the duration of the modelled scenarios. The EBITDA metric allows performance to be compared independently of financing and ownership structure, which vary widely between businesses (McLean and Holmes 2015) and is consistent with the approach of Stokes *et al.* (in press). Expenses include variable and overhead costs associated with running the beef herd, but general capital costs (e.g., depreciation of existing infrastructure and land) were not considered. Similarly, modelled income was generated from cattle sales, but did not include off-farm income, or the value of land and other assets. The GM and EBITDA are reported for the whole herd rather than on an AE basis because the CLEM model does not yet include an accurate calculation of AE that is consistent with industry standards (McLennan *et al.* 2020).

Several of the future scenarios involved large capital expenses such as oversowing forages or installing shade shelters, with the value of these investments assessed using net present value (NPV). The NPV was calculated using cash flow over 39 years using a 5% discount rate as per Bowen *et al.* (2020) and MacLeod *et al.* (2018).

3.2.2 Baseline model assumptions

The baseline enterprise for this case study is based on that used for the DCAP project (Bowen *et al.* 2020), adapted based on information from the literature and the regional reference group. The base property for this case study is 16,000 ha of Mitchell grass and associated native pastures, with a long-term carrying capacity of 2,000 adult equivalents (8 ha / AE) and a safe pasture utilisation rate of 22%. It is assumed that 5% of land area is covered by woody vegetation (both native and weedy) and is unavailable for grazing. This estimate was based on an initial estimate of average woody vegetation for the Cloncurry, Richmond and McKinlay Local Government Areas from the ANU Tree Change tool (ANU 2020) between 1990-2020 (Figure 6). The reference group considered the patterns of vegetation cover for this period to be realistic for the region but felt that average cover (2.4%) under-estimated impacts on grazing land, and so the value was increased.

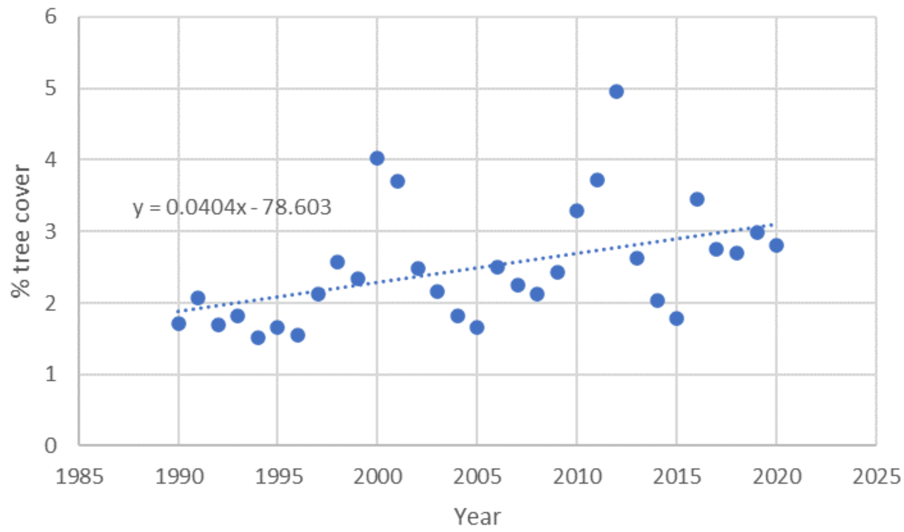

Figure 6. Average tree cover across the Cloncurry, McKinlay and Richmond local government areas between 1990 and 2020. Note that values are % of total land area, and the reference group estimate that % of grazing land would be higher. Source: ANU (2020)

A self-replacing *Bos indicus* crossbred breeding herd (~50% *B. indicus*) primarily grazes on the open grasslands, with urea-based non-protein nitrogen supplements offered during the dry season to reduce breeder liveweight losses. The maximum herd size set in the model is 1,100 breeders, though it is often less than this due to seasonal conditions. Cows are mated between January and May, with heifers joined from two years. Maiden heifers receive two injections of a leptospirosis vaccination prior to their first mating, with all breeders receiving an annual booster mid-late pregnancy (FutureBeef 2022). Bulls are vaccinated against vibriosis annually before joining. Cows are pregnancy tested in July, with empty cows removed from the herd, though we acknowledge that this is not universal practice. Calves are weaned in either June or September, with a target weaning weight of ≥180 kg liveweight and provided with good quality hay. Because the model runs on a monthly timestep, hay is provided for a whole month; whereas in practice, weaners are usually fed for 5-7 days in the yards before being turned out onto pasture (Tyler *et al.* 2012). Underweight animals at second round of weaning (< 150 kg) are supplemented with protein meal to bring them up to weight (Tyler *et al.* 2012).

The property turns off steers (sold into live export or domestic feedlot markets) and females that are culled for age or poor reproductive performance, or surplus to requirements. Land condition is maintained through drought years by destocking; a feed budget is done in May each year to estimate the amount of feed available and how many cattle can be maintained until the end of the dry season. The model assumes that the land manager aims to finish the dry season with at least 800 kg/ha standing biomass, and excess stock are sold. The herd is rebuilt through a combination of natural replacement and purchase of breeding animals.

As noted by Bowen *et al.* (2020) and other projects, cattle prices are highly variable within and between years, but the model set up necessitates the use of a single price for each class of cattle. CLEM, and other models, also require users to set specific sale times and criteria, so do not account for manager discretion in assessment of how the season is turning out and what markets are doing in deciding what animals to sell and when. For consistency, we used the average prices from 2014-2019 reported by (Bowen *et al.* 2020) (Table 1).

Table 1. Cattle sale prices based on Bowen *et al.* (2020). Prices are saleyard prices, exclusive of levies, commissions, trucking expenses etc.

Class	Price $ / kg liveweight
Restocker steer (200-330 kg)	2.87
Restocker heifer (200-330 kg)	2.45
Live export feeder steer (280-380 kg)	2.90
Light steer (330-400 kg)	2.71
Medium steer (400-500 kg)	2.53
Medium cow (400-520 kg)	2.03

Fixed and variable costs are based largely on Bowen *et al.* (2020) and McLean and Holmes (2015) (Table 2 & 3). Since the modelled herd size varies between years due to seasonal conditions and reproduction rates, contract mustering is included here as a variable cost based on herd size, rather than a fixed cost as in the DCAP report (Bowen *et al.* 2020).

Table 2. Annual fixed costs for baseline scenario

Item	Cost ($)
Accounting, administration, phone etc	10,000
Electricity and gas	5,000
Fuel and lubricants	25,000
General repairs and maintenance	25,000
Insurance	7,500
Motor vehicle expenses	15,000
Rates	15,000
Wages	20,000
Wages - owner	80,000

Table 3. Variable costs

Item	Cost
Contract mustering	$5 / head x 2 annual musters
Commission and insurance on cattle sales	3.5%
MLA levy	$5 / head sold
NLIS tags	$3.50 each
Leptospirosis vaccine	$1.30 / dose
Vibriosis vaccine	$10 / head for bulls
Pregnancy testing	$5 / head for all breeders
Hay	$300 / tonne landed on farm
Mineral mix	$1000 / tonne landed on farm
Protein meal	$855 / tonne landed on farm

3.2.3 Modelling of future climate impacts

Future climate files were obtained from the Queensland Future Climate Dashboard (Syktus *et al.* 2020), using a change factor approach to scale the baseline climate data (1980-2019). This data was modelled using:

- Median global warming sensitivity
- Intergovernmental Panel for Climate Change Assessment report 5 (AR5)
- Representative concentration pathway (RCP) 8.5

The Future Climate Dashboard provides the option to select from a range of global climate models (GCMs). Future climates were modelled using four composite models: HI, a high level of global warming, where the Eastern Indian Ocean warms faster than the Western Pacific Ocean; HP, a high level of global warming, where the Western Pacific Ocean warms faster than Eastern Indian Ocean; WI, a low level of global warming, where the Eastern Indian Ocean warms fasters than Western Pacific Ocean; and WP, low level of global warming, where the Western Pacific Ocean warms fasters than Eastern Indian Ocean (Figure 5). The reliability of the models for the Australian region has been ranked by an expert panel from CSIRO, the Bureau of Meteorology, and the (former) Queensland Department of Environment and Resource Management, with models from the HI and HP quadrats considered the most suitable.

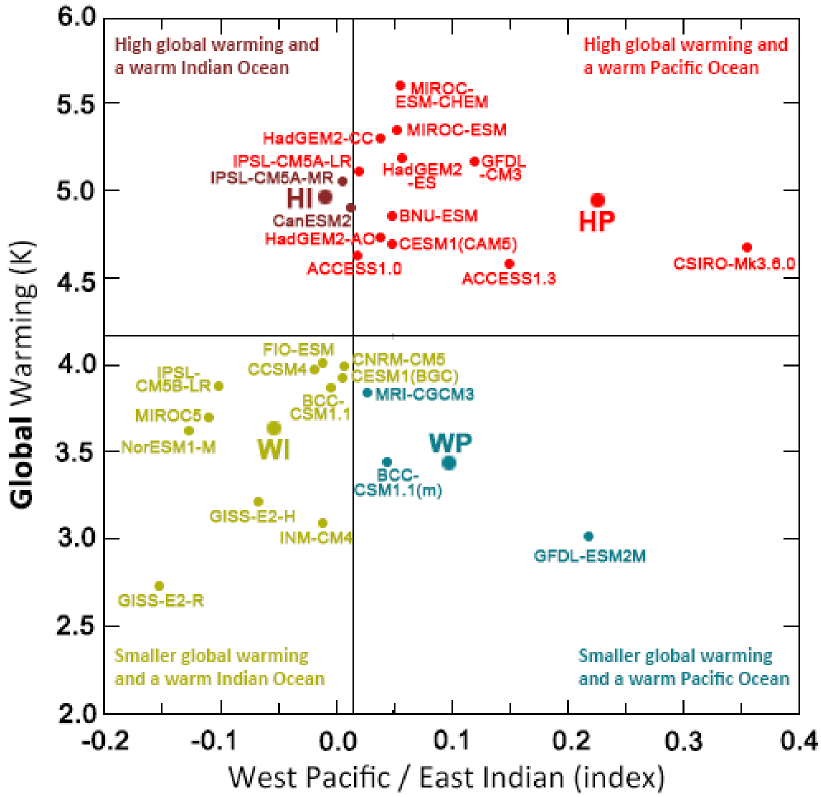

Figure 7. Waterson 4-way typology of GCMs for Australia. Future climates were modelled using the four composite models (HI, HP, WI, WP)

Across these models, projected changes for the Northern Downs region indicate that:

- CO_2 levels will increase – *very high confidence*
- Average temperatures will increase in all seasons – *very high confidence*

- More hot days and warm spells are predicted – *very high confidence*
- Changes to rainfall – *possible but unclear*
- Increased intensity of extreme rainfall events – *high confidence*
- Fewer, but more intense, tropical cyclones – *medium confidence*

The baseline enterprise was modelled under all climate scenarios, with no changes to animal management. Some adjustments to the CLEM model were required to capture how climate changes impact growth of pastures, woody vegetation, and livestock. These are summarised in Table 1 below, with more detailed explanation in the following paragraphs. The modelling does not capture impacts from changes in the frequency and intensity of extreme events.

Table 4. Description of how key climate change impacts are captured in the CLEM model.

Climate Impact	Implication	How handled in model
Increased growth of woody vegetation in response to increase atmospheric CO_2.	Reduced area for grazing, and reduced land values.	Area available for grazing decreased. Land value is not included in any bioeconomic modelling.
Changes in pasture production in response to changes in rainfall and increased temperatures and CO_2.	Changes in availability of pasture biomass. Possible changes in feed quality.	Changes in biomass are modelled by GRASP using future climate input files. Changes in feed quality were not modelled.
Increased incidence of heat stress in cattle in response to higher temperatures.	Reduced feed intake, which contributes to reductions in liveweight gain, reproduction, and survival.	Coefficient for maximum intake in model decreased.
	Increased mortality due to direct impacts of high heat loads.	Increased baseline mortality rate.
Increased frequency and intensity of extreme weather events.	Loss of pastures, livestock, and infrastructure.	Unable to be modelled.

Growth rates of native (e.g., Gidgee) and weedy (e.g., Prickly Acacia, Parkinsonia) woody vegetation are increasing in response to rising CO_2 but are limited by rainfall and soil nutrients (Archer *et al.* 2017). Reviews such as that of Stevens *et al.* (2017) report increases in woody vegetation at approximately 1.1% per decade in Australian savannas, but these are national averages that encompass a range of bioregions and include losses in vegetation due to land management, which offset increases in woody thickening and encroachment. The average increase in tree cover across the Cloncurry, McKinlay and Richmond local government areas between 1990 and 2020 is approximately 0.04% per year, with significant inter-year variation (Figure 6). Much of this variation is attributable to variation in rainfall rather than land clearing. However, we assume that the increase in woody vegetation would likely be higher in the absence of active control by land managers. The CLEM model does not allow for a dynamic change in land area between years, so an average value must be used. Using the slope from the data reported by ANU (2020), and the baseline tree cover of 5% in 2000, tree cover in the future climate scenarios was estimated to increase to 7% in 2050.

Changes in pasture yields were modelled directly in GRASP, but this model does not simulate any changes in feed quality. The nutritional value of pastures may decrease under future climates. However, we were unable to find any consistent information on how these parameters would likely change under the future climate scenarios, so no adjustments were made.

The herd model in CLEM runs independent of any climate inputs, and changes in animal production due to heat stress need to be manually manipulated. The biggest impacts of heat stress are via changes in feed intake, which is reduced in response to high temperature and humidity. While reductions in feed intake are greatest in *Bos taurus* cattle breeds, impacts on *Bos indicus* breeds are still likely. For example, Gaughan *et al.* (2010) reported decreases in feed intake of between 10-20% for unshaded *Bos indicus* cross cattle (~20-70% *Bos indicus* genetics) in feedlots under very hot and extreme heat conditions (heat load index >86). Reductions may be less severe under grazing conditions, but no published data is available to provide guidance on how much feed intake could change. Within CLEM, potential feed intake is calculated using equations published in the Australian Feeding Standards (Freer *et al.* 2007). A maximum intake based on animal type (0.025 kg dry matter intake per kg cattle liveweight) is adjusted for animal age, condition, physiological state, and feed quality. It is then further limited by feed availability. The maximum intake for cattle was reduced to 0.02425 for the baseline and 0.02275 for 2050 based on the approach of Thornton *et al.* (2022) and equations from Tedeschi and Fox (2020). These equations are not breed specific, so may overestimate reductions in feed intake by grazing *Bos indicus* cattle. However, breed specific equations are not available and the proportion of *Bos indicus* genetics in northern herds is variable.

Reductions in feed intake due to changes in pasture production and animal heat stress lead to reductions in liveweight gain and body condition score of cattle, which in turn reduce reproduction and survival rates. Reproduction and mortality can also be directly impacted by heat stress. However, it is difficult to find data to quantify these impacts above the losses attributable to reduced feed intake. A review of data from Northern Australian beef production systems by Burns *et al.* (2010) indicates that under current climates these losses may be small relative to other causes, with heat stroke responsible for just 0.5% mortality of calves. This is in contrast to Fordyce *et al.* (2023), who found that a temperature humidity index (THI) >79 for two weeks or more during the month of calving was associated with a 6.6% increase in mortality in the Northern Downs region, with smaller differences recorded in the Southern Forest and Central Forest regions. Several causes were hypothesised, including direct impacts of heat stress on the dam and calf, which could reduce milk production and increase dehydration.

The CLEM model allows users to specify a base mortality rate, which captures losses unrelated to nutrition, including disease, heat stress and predation. This rate was increased by 0.5 percentage units across the herd in the future climate scenarios to capture potential increases in animal losses due to heat stress and potential new biosecurity threats.

3.2.4 Opportunities to reduce greenhouse gas emissions

Activities that could potentially reduce greenhouse gas emissions or sequester carbon in the case study region in a northern, native grassland were identified using the LOOC-C tool (CSIRO 2020) and assessed for their feasibility and inclusion in the adaption scenarios (Table 5). Of the methods available, only beef cattle herd management was considered feasible and included in the modelled scenarios through changes to herd genetics, feedbase and culling rules. Future technologies, such as the use of a slow-release intra-ruminal device to deliver methane inhibiting compounds were also considered.

Table 5. Suitability of current Emissions Reduction Fund (ERF) methods for the northern downs case study region

Method	Description of activities	Suitability for case study region
Herd management	Reductions in emissions achieved through efficiency gains (i.e., fewer animals are required for a given level of output)	**Suitable** Practices are not specified, but could include improvements to pasture, herd genetics, or animal management to increase reproduction and growth rates.
Feeding nitrates	Fully or partially replacing urea supplements with nitrate supplements, which have a direct impact on enteric methane production.	**Not suitable** Trials in northern Australia have shown low and variable intake of nitrate supplements, with productivity decreases (Callaghan *et al.* 2020). Emissions intensity may increase using this method. Nitrate supplements are also expensive, and there is risk of toxicity.
Reforestation, regeneration and/or regrowth	Promoting growth of woody vegetation in areas that have previously been cleared for grazing. This could be through active tree-planting or excluding livestock from areas to allow regrowth.	**Not suitable** The Northern Downs case study region is naturally grassland. Woody vegetation may change water balance of landscape (Honda and Durigan 2016) and increase fire risk. Trees may not persist in this landscape due to soils and rainfall variability (Fensham and Fairfax 2005; Fensham *et al.* 2005) Grasslands may be a more reliable carbon sink as they are better able to withstand drought, rising temperatures and fire (Dass *et al.* 2018).
Soil carbon	Changes to land management practices to promote carbon storage in soils	**Not suitable** Many of the practices described in this method are not suitable for extensive northern systems (e.g., application of nutrients). Trials on Mitchell grass pastures have shown year to year variability in temperature and soil moisture overwhelm any responses to changes in land management (Allen *et al.* 2013; Bray *et al.* 2016; Orr and Phelps 2013; Pringle *et al.* 2014).

While many of the options reviewed were unsuitable for the Northern Downs region of Queensland, they may be feasible in other extensive grazing systems. For example, analysis of soil carbon at the Wambiana grazing trial did find differences in soil carbon stocks between stocking rate treatments (Pringle *et al.* 2011). The vegetation at Wambiana is predominantly savanna woodlands (forest country), and trees and shrubs had a greater contribution to soil carbon stocks than perennial grasses at that site.

3.2.5 Adaptation scenarios

Four scenarios to adapt to future climates were derived from discussion with the reference group. To provide consistency with the other NEXUS case studies, these scenarios were:

- **Adaptation** of the current farm system
- **A sustainable future** focusing on opportunities to mitigate and/or offset emissions
- **Diversification** of farm activities or enterprise mix
- **Transformation** of the farming enterprise

The first three scenarios focus on incremental changes, and the application of technologies or activities currently available to producers, or which could conceivably be available by 2030. For the *Transformation* scenario we combine a selection of 'best bet' options from the first three scenarios that have the greatest potential to increase the productivity, profitability, and sustainability of beef systems in this region. We also explore novel methods of implementing these activities.

Adaptation options investigated across the four scenarios spanned the themes of feedbase, animal genetics and management, and future technologies, though not all themes were represented in each scenario (Table 6). These activities plus other potential changes identified by the reference group are also discussed in the industry interviews as part of the research into adaptive and transformational capacity.

Table 6. Modelled scenarios for future beef systems.

Theme	**Changes to farming system**		
	Feedbase	**Animal genetics & management**	**Future technologies**
Adaptation	Additional investment into **control of woody vegetation** means that there is no change in grazing land area between the baseline and future climate scenarios. In this scenario, woody vegetation is controlled using existing, labour-intensive, methods.	**Increased fertility** through improved genetics (use of EBVs, stricter culling of non-pregnant cows). **Heat stress avoidance** through changes in timing of animal management activities. **Improved growth efficiency** through genetic gain (use of EBVs).	**Remote monitoring** of water points, fence lines and other infrastructure.
A Sustainable Future	New **legume species** is oversown to reduce methane production and increase feed available. **Maintenance of woody vegetation,** accompanied by a reduction in grazing area.	**Reduced methane production** via improved efficiency of production (increased fertility and growth efficiency through improved genetics) and anti-methanogenic properties of novel pasture species.	-
Diversification	-	**Change in herd structure** from breeding herd to steer turnover.	-
Transformation (for both breeding herd and steer turnover operations)	**Oversowing legume** to increase pasture quality and availability. **Control of woody vegetation** using novel methods.	**Reduced methane production** via vaccine and improved production efficiency (increased fertility and growth efficiency through improved genetics).	**New methods to control woody weeds** - drones or bio control. **Drones** to monitor and move cattle.

		Heat stress avoidance through changes in timing of animal management activities.	

Feedbase adaptation options included increases or decreases in woody vegetation and new pastures to improve productivity and reduce methane emissions. Changes to the area of woody vegetation were implemented by adjusting the total grazing area available. In the *Adaptation* scenario, it is assumed that woody vegetation can be controlled at current levels using existing methods such as manual removal and handspraying, with the cost of control taken from Bowen *et al.* (2020). In the *Transformation* scenario, control of woody vegetation is achieved through novel methods such as herbicide application by drones. These methods would reduce the labour intensity of control and may be more effective. In the *Sustainable Futures* scenario, native woody vegetation is allowed to naturally increase, but weeds such as Pricky Acacia are still controlled. The rates of increase are difficult to predict, and no data is available to indicate the rate of increase for different vegetation types in this region. We assume that average woody vegetation increases to cover 7% of grazing land by 2050.

Oversowing legumes improves animal production by increasing pasture quality and availability. Following the approach of Ash *et al.* (2015), this was achieved in the model by increasing grass basal area from 3% to 5%, reducing the N decay rate from 0.35 to 0.15, and reducing the dry matter digestibility decay rate from 0.11 to 0.10. These changes reflect the increased forage growth and year-round higher feeding value of legume-augmented pastures. The increase in pasture quality and availability would increase the carrying capacity of the property. However, this was not targeted in the *Sustainable Futures* scenario because one of the main aims of this scenario was to decrease greenhouse gas emissions. Instead, it was anticipated that the legume would increase reproduction and growth rates and provide a feed bank as a buffer for dry years. This lower pasture utilisation would also assist in long-term persistence of a legume in a Mitchell grass pasture (Gardiner *et al.* 2004). Costs of legume establishment were based on those reported for faecal seeding of Desmanthus (Agrimix 2023) and set at $50/ha.

The inclusion of new legume pastures in the *Sustainable Future* scenario was anticipated to reduced methane emissions through increases in the efficiency of production and a direct reduction in enteric methane production. In pen feeding studies, Suybeng *et al.* (2020) demonstrated a 10% reduction in methane production in cattle fed Rhodes grass hay (70% of daily dry matter intake) and Desmanthus (30% of daily dry matter intake). There was no benefit at lower levels of inclusion. For our modelling, we assume that Desmanthus (or an equivalent species) is consumed at 20% diet, but that selective breeding increases anti-methanogenic properties, so that the average decrease in enteric methane production is 5% across the herd. In our model, this reduction in methane production was achieved by scaling the methane production coefficient of Charmley *et al.* (2016) (20.7 g methane/kg DM intake) by an equivalent amount (i.e., to 19.7 g methane/kg DM intake). In the *Transformation* scenario, it was assumed that the availability of a slow-release bolus would provide further reductions in enteric methane fermentation. This technology is currently being developed, and it is anticipated that a device providing a 50% reduction in enteric methane and lasting at least 180 days would be available by 2050. Current methane inhibiting additives (i.e., Bovaer®, Asparagopsis) cost between $0.30 - $1.00 per head per day, but we assume that improvements in the scale and efficiency of production will reduce this substantially over the coming decades, and a cost of $0.10 per head per day is used in our analysis.

Animal adaptation options focused on changes to animal management and genetics to improve the efficiency of production and reduce the impacts of heat stress. Herd fertility was increased through application of stricter culling rules and use of EBVs. The CLEM conception curves were adjusted to increase conception rates of cows in lower body condition (Ash *et al.* 2015), and all non-pregnant cows and heifers were culled. Improved growth efficiency through genetic gain was achieved by adjusting the growth coefficient (Ash *et al.* 2015). Avoidance of heat stress could be achieved by changing the timing of animal management activities (e.g., by undertaking husbandry activities at cooler times of the day, or even at night using drones with thermal imaging technology), and through provision of additional natural or artificial shade. Preliminary data from on-going research on the Barkly Tablelands (McCosker 2023) has shown that the provision of artificial shade near water points tended to decrease calf mortality in first-calf cows, though this was not statistically significant, and the differences varied between years (0.7 – 9.6%). Due to the extensive nature of production, it is assumed that impacts of heat stress can be reduced, but not eliminated, so the maximum feed intake coefficient and base mortality rates for the whole herd were set to midway between the current and 2050 values. The cost of shade structures was estimated to be $30,000 (McCosker *pers comm*), with a lifespan of 40 years. The start of joining was delayed from January until February, and still finished in May, though could be delayed even further based on responses from the industry interviews.

There are few scalable options for diversification of beef enterprises in the Northern Downs region due to local environmental conditions and distance to markets. In the interviews and reference group discussions, many producers noted the important of off-farm income. However, these opportunities are varied, based on personal skills and preferences. Other options for diversification that were discussed included irrigated agriculture or opportunistic dryland cropping. While there are some examples of irrigated and dryland agriculture occurring, these require large scale clearing of native grasslands, which may cause a loss of soil carbon and biodiversity, making it incompatible with the aims of this project. There are also already many other studies that have assessed the viability of irrigated agriculture across northern Australia, including in the Flinders River catchment (Petheram *et al.* 2013). Thus, instead of evaluating alternative business opportunities, for the *Diversification* scenario we model the impacts of changing the herd structure. In this scenario, the breeding herd was replaced with a steer turnover operation, similar to that described by Bowen *et al.* (2020). In years with sufficient biomass (>1500 kg DM/ha in May), 1500 weaner steers (6 months old, 180 kg) were purchased and then managed as per the steers in the baseline scenario. No changes were made to fixed costs (Table 2), which were applied in all years, regardless of if cattle were present.

Future technologies included in the scenarios were sensors to facilitate remote monitoring of water points, and the use of drones for cattle monitoring, mustering and weed control. The costs of remote water monitoring technology for the *Adaptation* and *Transformation* scenarios were based on the values provided in the FarmBot product guide (FarmBot 2021) (Table 7), assuming devices were installed on six water points (2500 ha per water point (Phelps 2012)). A water level sensor was installed on each water point, with an annual satellite subscription for each device. The savings in labour, fuel and vehicle maintenance were estimated using the online tool available on the FarmBot website. The cost of purchasing drones was informed by SkyKelpie (https://www.skykelpie.com/), an aerial stockmanship company operating in the Northern Downs region (Table 7), with two drones used to muster cattle and monitor animals, fence lines etc. Costs included the purchase of drone hardware (e.g., drones, controller, batteries, chargers etc), software for mapping and route planning, and licensing of operators. Drone use is currently limited by challenges such as battery lifespan and line of visual sight rules, but it is assumed these can be overcome by 2050.

It was difficult to find information on the lifespan of the remote water sensors and drone technology, but it was assumed to be 5 years for both.

Table 7. Cost of future technology

Item	Cost
Tank water level sensor	$1,290 per sensor
Satellite subscription	$1.20 / day per sensor
Drone hardware	$10,000
Remote pilot license & training	$1,750 per operator
Drone software (mapping, route planning etc)	$1,600 per year

3.3 Understanding adaptive and transformational capacity

Interviews were conducted with eight red meat producers from the Northern Downs region about their past experiences with adapting to extreme weather events and their perspectives on future adaptations to the regional climate.

An understanding of the biophysical and economic dimensions of agricultural systems under a changing climate is important in building the knowledge basis for adaptation and transformation in the Australian red meat sector. However, it is also critical to explore the human and social aspects of adaptation/transformation and what they mean for 'how adaptation [and transformation] can be realized in practice' (O'Brien and Hochachka 2010). For example, a key risk is that technologically feasible adaptation pathways remain largely conceptual and the desirability of and commitment to their implementation by scientists, policy makers and practitioners is unexplored or unknown (Boyd 2017). This is why it is critically important to engage directly in climate change adaptation research (CCAR) with producers and other industry professionals through their participation in projects, such as NEXUS, and through gathering social data on the constraints and opportunities for adaptation and/or transformation in practice (Davidson 2016; Sietsma *et al.* 2021).

Adaptive capacity is based on the resources or set of capitals (natural, physical, political, social, financial) available to adapt to change such as climate extremes as it occurs (which is resilience), and the capability to deploy these resources to adapt appropriately (Leith and Haward 2010; Nelson *et al.* 2007). These five capitals are often used to assess the 'generic' adaptive capacity, that is, the factors required to adapt to a (generic) range of threats (Mortreux and Barnett 2017). In effect, adaptive capacity is about the level of resources the individual or system has, and whether they can deploy them to enable resilience, and take advantage of opportunities as they emerge. Additional factors such as having appropriate institutional and governance networks are recognised as essential for enabling adaptation (Preston and Stafford-Smith 2009).

It is important to note that such resources or capitals do not operate independently (Smit and Wandel 2006). The adaptation process involves the interaction of capitals and elements of the different capitals. For example, a farm's infrastructure and utilization of digital technologies, (the physical capital), has served to replace labour or alternatively attract and retain the agricultural workforce, (the human capital) (Nettle *et al.* 2018). The adaptive capacity of individuals or system is affected by interactions between financial, policy and physical factors, and individuals, communities, and regions (national and international). Leith and Haward (2010) emphasize the implication of these definitions is that adaptive capacity is as much about the process and relationships as it is about the individual, community, or industry. In this way, adaptive capacity is dynamic and context specific (local resilience) (Barlow *et al.* 2010). While social and experiential learning can be cultivated over time, and other capitals can be boosted since adaptive capacity is something constructed (Nettle *et al.* 2018), there will inevitably be stresses that will place a limit on adaptive capacity. It is not infinite (Rickards 2014).

Assessments of adaptive capacity for responding to environmental change (e.g., climate change) have typically drawn on this assets-based theory where there is often a greater focus on the financial capital. Scholars and practitioners have argued that this approach can constrain our understanding of what is required for adaptation and have proposed frameworks that also consider other aspects such as social organisation, learning, flexibility, socio-cognitive constructs and agency (Barnes *et al.* 2020). Furthermore, (Mortreux and Barnett 2017) contend that an assets-based assessment of adaptive capacity would benefit from expanding the assessment framework to include psycho-social attributes necessary for adaptation such as risk-taking behaviour, perceptions of weather variability, skills for planning, and interest in change. Assessing the adaptive capacity within this new approach offers the opportunity to capture the mobilization of assets or how capitals are translated into action by individuals or systems. This is to overcome the tendency of assessments to describe the intention for adaptation only. The approach and analysis of the producer interviews has drawn on the work of Barnes *et al.* (2020), in recognition of these recent developments in adaptive capacity theory and practice.

Barnes *et al.* (2020) have tested an adaptive capacity assessment framework with a remote island community located in tropical Papua New Guinea. This framework focuses on human, social and social-ecological aspects of adaptation as a complimentary method to a financial-asset based approach (Table 8).

Table 8. Adaptation of Barnes *et al.* (2020) six domains of adaptive capacity with indicators and description used for the analysis of the producer interviews.

Adaptive capacity domain	Indicators –examples that can be drawn from the producer interviews	Description
Agency	Descriptions of proactive decision making and deciding if, how and when a producer has responded to change.	Power to influence change or to make free choices in determining whether to change (or not).
Assets	References to using or needing financial resources to make changes or respond to change.	Access to financial resources such as cash, savings, refinancing potential, capital.
Flexibility	Descriptions of changing strategies, practices, or decisions based on learning and experiences.	Willingness and ability for changing strategies (e.g., moving between livelihoods or between techniques and practices within livelihoods), part of reflexive practice and adaptive management.
Learning	Descriptions of lessons learned from past experiences, identifying knowledge gaps and aspirations for future learning opportunities.	Different forms of learning: educational courses and training (formal), learning in social settings (social), learning from experiences and direct observation (experiential).
Organisation	Reference to specific people or organisations that are used for information, knowledge, advice, or other forms of support to undertake adaptation and practice change.	Social ties bind us to others and shape processes of social influence, such relationships determine whether and how information, resources and support are accessed, social and social-ecological relationships also provide the context in which people recognise change, make sense of their experiences, and prepare to take strategic action for adapting to shocks/uncertainties.

Socio-cognitive constructs	Statements or comments that indicate approaches towards risks, beliefs in climate change, attitudes about the need to change (or not).	Risk attitudes or cognitive biases that influence perceptions regarding the need to adapt to change (or not) and the costs and benefits of adaptation.

3.3.1 Qualitative data Collection

The design and administration of semi-structured interviews (or interview guide approach) was used as the key data collection method to inform the prospective pathways for delivering required industry skills, capacities, and capabilities to facilitate adaptation in the red meat sector. This method is useful for understanding complex issues, such as adaptation to climate change. By using an interview guide to structure and sequence the questions, the data is collected with a level of rigour. However, the flexibility to change the wording or sequencing of questions, can reduce the comparability of responses (Patton 2015). The interactive nature of the semi-structured interview reflects the conversational style of social exchanges in a real-world setting. The interviewee has an opportunity to describe their experiences in their own words about the topic(s) of interest. The interviewer is also able to continually prove the interviewee's responses to gain clarity and deeper understanding of the topic of interest during the interview. Therefore, it is an appropriate technique for drawing out the red meat producer's experiences in and perspectives on adaptation.

3.3.2 Selection criteria and recruitment of interviewees

Interviewees were purposively selected (Guarte and Barrios 2006) based on five key conditions: 1) gender balance, 2) older and younger producers, 3) operating within the case study region, 4) balance of Reference Group Members with Non-Reference Group members, and 5) at least one corporate operation. We wanted to be able to present the views of producers as women and men in equal numbers to avoid a gender bias to the data. We also wanted to ensure we were capturing the views of adult producers that were under 40 and over 40 to avoid an age bias to the data. It was important to select interviewees both within the NEXUS Regional Reference Group and non-Reference Group members to test if the perceptions of the adaptation pathways were similar within and outside the Regional Reference Group. Although most of the interviewees were owner operators of a family livestock business, we selected one corporate beef business to provide some preliminary insights into the adaptive capacity of a large, company run operation. While the purpose of the semi-structured interviews focused on the red meat producers primarily, we also interviewed a representative of MLA, to provide an industry perspective on what adapting to climate change means at a strategic level. The results from this interview are not presented in this report, however this interview material has been considered in the recommendations for prospective pathways for adaptation support.

The recruitment of potential interviewees was coordinated by a QDAF Senior Extension Officer who worked in the Southern Gulf region. Each interviewee was given a $50 gift voucher as a token of appreciation for providing their time.

3.3.3 Interview process

The interview questions were based on a general inquiry into the adaptive capacity of producers to form the basis for recommending prospective pathways to deliver required industry skills, capacities, and capabilities to facilitate industry adaptation. The interview was designed in two parts. The first part included standard questions to develop an on understanding of the past adaptation actions taken by producers in response to extreme weather events. The second part was focused on the four adaptation pathways being modelled for the NEXUS CSIRO project. The standard questions were focused on the motivations and enablers for implementing the ‘adapt’, ‘diversify’, ‘towards carbon neutral (sustainable futures)’ and ‘transformational’ pathways as options for adaptation. Supplementary questions investigated how interviewees perceived the pathways in terms of risk, how the wider population of producers in the region might perceive these pathways and who should lead the development and adoption of these pathways. Supplementary questions were asked when there was enough time during the scheduled interview.

Interviews were conducted remotely either by mobile phone or using video conference software. All mobile interviews were audio recorded with permission of the interviewees. On average the interviews were approximately one and a half hours, with one interview lasting over two and half hours. Each interviewee was emailed a transcript of their interview to provide the opportunity to edit the transcript, delete or add text.

The interview data was transcribed from the audio recordings using a professional transcribing service. The transcripts were then coded using NVIVO 12 plus software for thematic analysis based on the six dimensions of adaptive capacity (Barnes *et al.* 2020), allowing dominant themes to be identified in terms of motivations, enablers, and inhibitors for implementing adaptive pathways.

4 Results

4.1 Modelling of the case study enterprise under current and future climates

Inter-annual variation was high in all scenarios, with annual biomass production ranging from almost zero in drought years, to over 4000 kg/ha. Annual biomass production (mean ± standard deviation) modelled under the warm Indian Ocean scenarios (WI 1,863 ± 1,185 kg/ha, HI 1,799 ± 1,148 kg/ha) was similar to the current baseline (1,827 ± 1,189 kg/ha) (Figure 8). Slightly lower average annual yields were modelled under the warm Pacific Ocean scenario (WP 1,683 ± 1,090 kg/ha, HP 1,537 ± 1,062 kg/ha), but differences in average pasture production between the baseline and future climate projections are substantially less than the standard deviation.

Figure 8. Box and whiskers plots showing range of annual biomass production (kg/ha) under current (baseline) and 2050 climates modelled using four composite GCMs. X indicates average annual biomass production.

Average herd size was generally correlated to average biomass production; because CLEM does not accurately output AE numbers, this is reflected throughout the report as number of breeders at the start of joining (January) (Table 9). The weaning rates reported in Table 9 are calves weaned as a proportion of cows mated and are within the range of those reported elsewhere for the region (e.g., 65% Bowen *et al.* (2020), 72% McGowan *et al.* (2014)). The reference group noted high regional and inter-annual variability, even between the small number of properties they represented. Average calf loss across all climate scenarios was 11% from conception to weaning.

Table 9. Average annual productivity of baseline enterprise under current and future climate scenarios centred on 2050

	Current climate	WP	WI	HP	HI
Breeder numbers at start of joining (heads)[1]	778	674	773	662	777
Weaning rate[2] (%)	68	67	68	67	69
Beef production (kg liveweight sold)[3]	216,987	177,148	204,122	174,707	199,628
Pasture utilisation (%)	21	17	20	19	21
GM ($)	362,316	272,859	335,600	276,758	318,596
EBITDA ($)	159,816	70,359	133,100	74,258	116,096
Proportion (%) of years with negative EBITDA	16	57	41	56	19
Enteric methane (kg CO_2e/ha/year)	125	102	121	100	121
Enteric methane (kg CO_2e/kg liveweight sold)	9.2	9.2	9.4	9.2	9.7

[1] Breeders includes all cows and heifers of breeding age.

[2] weaning rate is calves weaned as a percentage of cows available for mating.

[3] kg liveweight sold includes culled cows, excess breeders and stock sold during de-stocking as well as steers.

Across all future climates, models with a warming Pacific Ocean present a more challenging future, while models with a warming Indian Ocean present a more favourable future. The volume of liveweight sold decreased by 6-19% across all scenarios, with the biggest decreases in the WP and HP future climates. These changes are driven primarily by the decrease in pasture availability (Figure 9). The decrease in grazing area in response to increased woody vegetation had little impact on herd size or productivity and may be underestimated in our modelling. There are likely large variations in the level of woody biomass between different properties. The current modelling also does not account for economic impacts through potential changes in land value.

Profit metrics followed the same trend as kg liveweight sold, with decreases across all future climates (Table 9). The decrease in profit, measured as EBITDA, was over 50% in the WP and HP scenarios. The WP, WI and HP future climate scenarios also showed an increase in the number of years with a negative EBITDA, reflecting an increase in the number of years with reduced (or no) stock turnoff to offset overhead costs. Despite similar economic assumptions, the GM for the baseline is lower than that reported by Bowen *et al.* (2020) due to smaller average herd sizes.

Total methane production (represented as CO_2e per ha over 16,000 ha) was related to herd size, decreasing under all future scenarios. There was little variation in emissions intensity per kg liveweight sold, though emissions tended to be higher (per kg liveweight sold) in the WI and HI future climate scenarios.

4.2 Exploration of adaptation scenarios

Activities modelled in the *Adaptation* scenario (i.e., reducing grazing land lost to woody vegetation, improved reproduction and growth rates through genetic selection, heat stress avoidance) provided an increase in liveweight sold of between 4-14% over the future climate baseline, and a 7-44% increase in profit (EBITDA) (Table 10). Under the WI and HI climate projections production was similar to the current baseline, but profit was still lower. Methane emissions per ha were higher than the future climate baseline due to an increase in average herd size, but the combination of activities provided a decrease in methane per kg liveweight sold, representing an increase in production efficiency.

To our knowledge, impacts of heat stress management have not been previously assessed, and the increase in productivity that can be achieved will be highly dependent on the availability of practical options for extensive grazing systems; especially those based on grasslands without high levels of naturally occurring shade. In addition, in our modelling the start of joining was only delayed by one month. Interviews with producers indicated longer delays could be considered and may provide greater benefits.

Table 10. Modelled outputs from the *Adaptation* scenario

	WP	WI	HP	HI
Breeder numbers at start of joining (heads)[1]	734	803	679	768
Weaning rate (%)[2]	70	69	69	69
Beef production (kg liveweight sold)[3]	199,757	219,667	189,921	207,850
Pasture utilisation (%)	20	19	18	19
Gross Margin ($)	307,934	349,450	303,558	337,817
EBITDA ($)	101,186	142,702	106,810	141,069
Proportion (%) of years with negative EBITDA	52	45	54	48
Net Present Value over 10 years	1,082,374	1,880,403	1,113,462	1,161,715
Enteric methane (kg CO_2e/ha/year)	112	124	102	117
Enteric methane (kg CO_2e/kg liveweight sold)	9	9.1	8.6	9

[1] Breeders includes all cows and heifers of breeding age.

[2] Weaning rate is calves weaned as a percentage of cows available for mating.

[3] kg liveweight sold includes culled cows, excess breeders and stock sold during de-stocking as well as steers.

In the *Sustainable Futures* scenario, improvements to the feedbase provided substantial increases in productivity (27-45% across GCMs) (Table 11) of similar scale to that modelled by Ash et al. (2015) (37% increase in beef turned off). Improving the feedbase increased the carrying capacity of the modelled property, with the average number of breeders increasing relative to both the current and 2050 baselines across all scenarios. The lower utilisation rate compared to other scenarios indicates that a higher carrying capacity may be possible in some years. Profit was also increased compared to both baselines, and the number of years returning a loss also decreased. However, EBITDA was still negative in 17-34% of years, indicating that improving the feedbase cannot completely overcome the challenge of a highly variable climate. The increase in herd numbers also meant that total methane emissions (kg CO_2e/ha) increased in this scenario, though methane intensity remained similar to the baseline due to improvements in efficiency.

Table 11. Modelled outputs from the *Sustainable Futures* scenario

	WP	WI	HP	HI
Breeder numbers at start of joining (heads)[1]	953	969	911	1013
Weaning rate[2] (%)	70	70	70	70
Beef production (kg liveweight sold)[3]	256,280	258,432	244,073	270,144
Pasture utilisation (%)	17	16	18	17
Gross Margin ($)	437,776	443,485	417,591	473,533
EBITDA ($)	235,276	240,985	215,091	271,033
Proportion (%) of years with negative EBITDA	25	21	34	17
Net Present Value over 10 years	741,653	1,059,662	1,360,134	1,612,943
Enteric methane (kg CO_2e/ha/year)	150	151	142	159
Enteric methane (kg CO_2e/kg liveweight sold)	9.3	9.4	9.3	9.4

[1] Breeders includes all cows and heifers of breeding age.

[2] weaning rate is calves weaned as a percentage of cows available for mating.

[3] kg liveweight sold includes culled cows, excess breeders and stock sold during de-stocking as well as steers.

The potential benefits of improving the feedbase have been noted in previous reports (e.g., Ash *et al.* (2015)). However, the lack of forage species that can persist in a highly variable climate is a challenge that needs to be overcome. Trialling new pastures can be risky, and previous failed attempts have discouraged many producers. Faecal seeding represents an opportunity to introduce new species without needing to invest in new machinery or land development and is suitable for hard-seeded species such as Desmanthus and Stylosanthes (Gardener *et al.* 1993). While not captured in our modelling, the more frequent occurrence of extreme events such as the 2019 floods is likely to exacerbate challenges associated with maintaining a productive feedbase.

The *Diversification* scenario also indicated opportunities to improve productivity and profitability, whilst reducing greenhouse gas emissions (Table 12). In this scenario, the volume of liveweight sold was increased by 183-222% compared to the 2050 baseline, and profit (EBITDA) increased by 30-86%. This is consistent with the results of Bowen *et al.* (2020), who found that switching from a breeding to steer-turnover operation was one of the most profitable options for the Northern Downs region. The GM reported here was lower than that reported by Bowen *et al.* (2020) because steers were only purchased in years when there was adequate biomass to support liveweight gains. This is reflected by the high proportion of years with a negative EBITDA, with fixed costs outgoing in all years, even when no animals were purchased. While the purchasing rules in our model were overly simplified (i.e., purchasing 1500 weaner steers in years with >1500 kg DM/ha), a more nuanced approach enabling purchasing of smaller cohorts of steers may be more profitable. Both total emissions (kg CO_2e/ha) and emissions intensity (kg CO_2e/kg liveweight sold) were substantially lower in this scenario compared to both the current and 2050 baselines due to the change in herd structure.

Table 12. Modelled outputs from the *Diversification* scenario

	WP	WI	HP	HI
Beef production (kg liveweight sold)[1]	570,203	578,203	558,342	584,443
Pasture utilisation (%)	16	17	20	16
Gross Margin ($)	333,666	375,541	312,090	352,997
EBITDA ($)	131,166	173,041	109,590	150,497
Proportion (%) of years with negative EBITDA	44	39	46	44
Enteric methane (kg CO_2e/ha/year)	95	97	92	98
Enteric methane (kg CO_2e/kg liveweight sold)	2.7	2.7	2.6	2.7

[1] kg liveweight sold includes culled cows, excess breeders and stock sold during de-stocking as well as steers.

As noted in other studies, the stacking of activities and technologies provided the greatest increase in productivity, profitability, and sustainability (Table 13 & 14). The *Transformation – breeding herd* scenario provided a 33-54% increase in kg liveweight sold, and a 62-202% increase in profit (EBITDA). Under the *Transformation – steer turnover* scenario, productivity increased by 195-248%, and profit by 172-419%. These changes were driven by the improved feedbase and novel methods to decrease enteric methane. Transitioning to a steer turnover operation provided bigger benefits than running a breeding herd, but the breeder herd was still viable when compared to the current and 2050 baselines (Figure 9 & 10). The profitability of the breeder herd was lower than in the *Sustainable Futures* scenario due to the cost of future technologies, particularly the methane-inhibiting boluses.

While it is possible the cost of this technology will decrease by 2050, the cost may still be worth it if it allows access to markets that expect low-methane products.

Table 13. Modelled outputs from the *Transformation – breeding herd* scenario

	WP	WI	HP	HI
Breeder numbers at start of joining (heads)[1]	981	961	910	1025
Weaning rate[2] (%)	70	70	70	70
Beef production (kg liveweight sold)[3]	272,889	272,383	253,817	285,492
Pasture utilisation (%)	16	14	19	17
GM ($)	404,486	408,082	373,295	433,252
EBITDA ($)	212,399	215,995	181,208	241,165
Proportion (%) of years with negative EBITDA	23	22	34	17
Net Present Value over 10 years	1,250,923	1,090,398	860,308	1,085,208
Enteric methane (kg CO_2e/ha/year)	80	79	74	85
Enteric methane (kg CO_2e/kg liveweight sold)	4.7	4.6	4.7	4.8

[1] Breeders includes all cows and heifers of breeding age.

[2] Weaning rate is calves weaned as a percentage of cows available for mating.

[3] kg liveweight sold includes culled cows, excess breeders and stock sold during de-stocking as well as steers.

Table 14. Modelled outputs from the *Transformation – steer turnover* scenario

	WP	WI	HP	HI
Beef production (kg liveweight sold)[1]	614,712	602,815	608,842	600,786
Pasture utilisation (%)	12	10	15	11
GM ($)	557,034	554,695	554,148	564,768
EBITDA ($)	364,947	362,608	362,061	372,681
Proportion (%) of years with negative EBITDA	20	17	19	15
Net Present Value over 10 years	2,561,999	2,327,077	2,355,560	2,036,716
Enteric methane (kg CO_2e/ha/year)	56	55	56	56
Enteric methane (kg CO_2e/kg liveweight sold)	1.5	1.5	1.5	1.5

[1] kg liveweight sold includes culled cows, excess breeders and stock sold during de-stocking as well as steers.

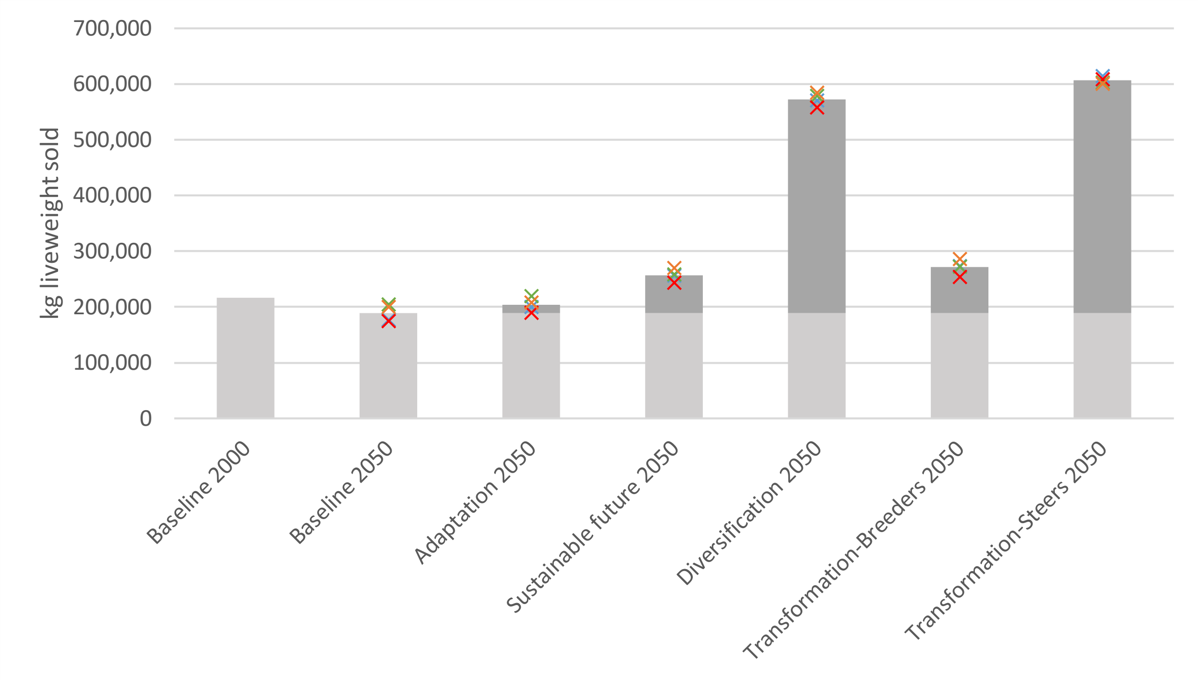

Figure 9. Average annual beef production (kg liveweight sold) for all modelled scenarios. Crosses indicate values from each of the four climate futures (WP blue; WI green; HP red; HI orange), with bars showing average values. The darker shading indicates the increase in production above the baseline management system modelled under future climates.

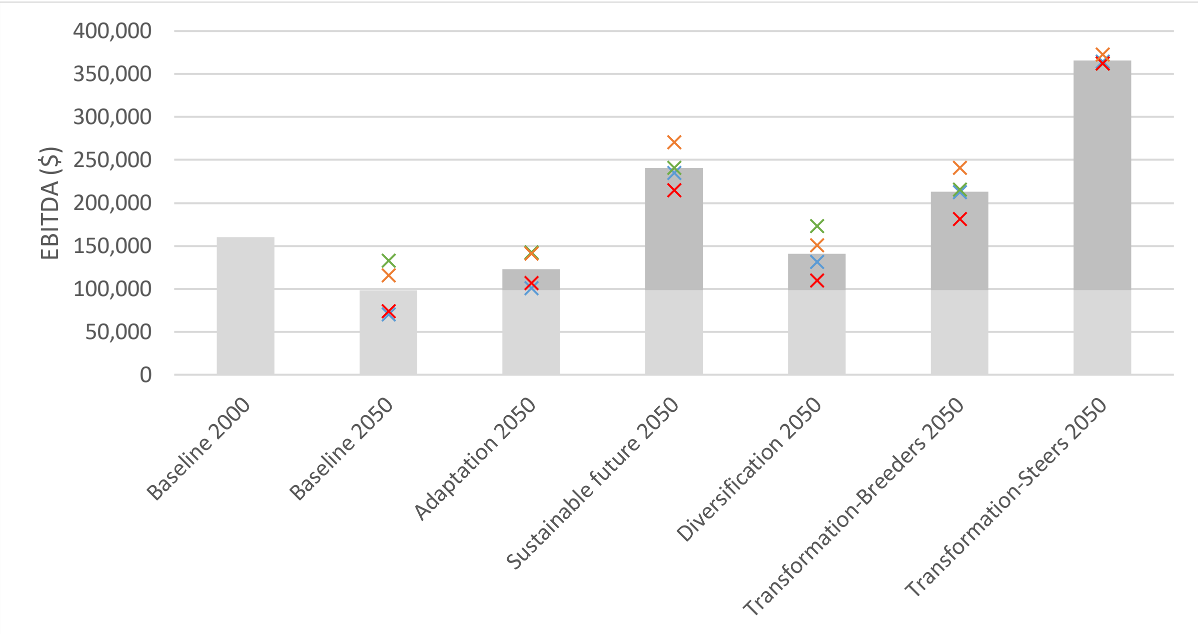

Figure 10. Average annual profit (EBITDA) for all modelled scenarios. Crosses indicate values from each of the four climate futures (WP blue; WI green; HP red; HI orange), with bars showing average values. The darker shading indicates the increase in profit above the baseline management system modelled under future climates.

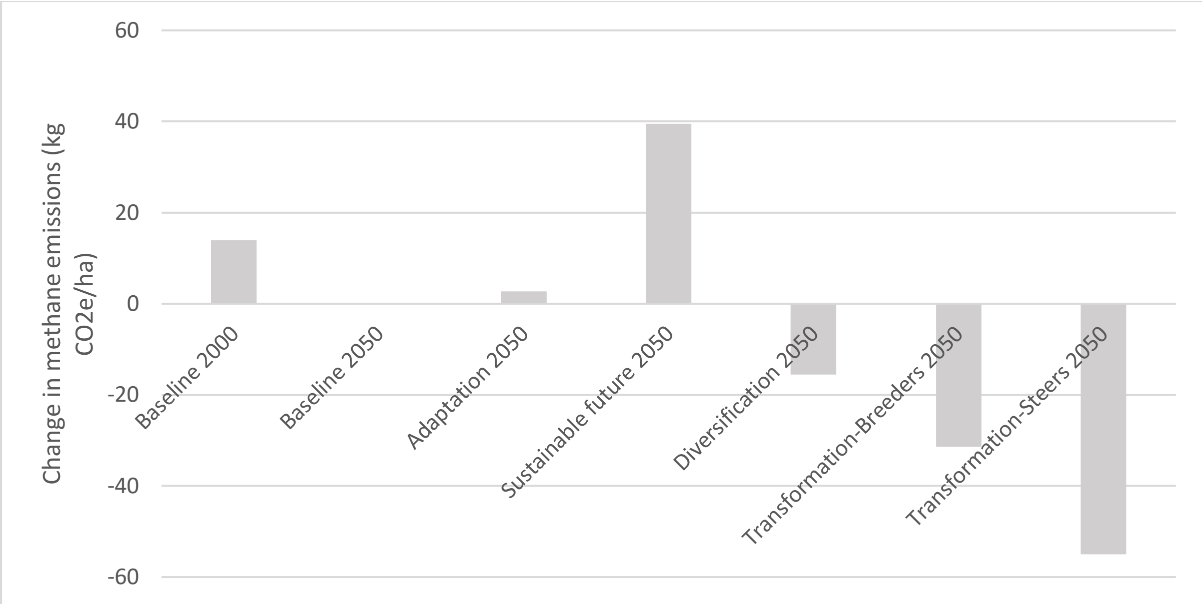

Figure 11. Average change in annual enteric methane emissions (kg CO_2e per ha) relative to 2050 baseline

4.3 Assessment of adaptive and transformational capacity

The following results are summarised and presented in three parts:

1. Producer experiences with adapting to extreme weather events in the recent (last 10 years),
2. Producer perspectives on adapting in the future (out to 2050) based on the four adaptation pathways,
3. Examples of adaptive capacities from the producer interviews.

It is useful to note that at the time of the interviews, producers were operating in conditions where cattle prices were at record highs and drought conditions were still persistent post recent flood event (2019). All names have been changed to protect the privacy of individuals.

The key messages across the three summary parts are:

- The consideration of the modelled adaptation pathways will be an individual decision-making journey for each producer based on their own farm system context, a unique combination of adaptive capacities and specific circumstances that prompt or trigger change.
- It is critical to develop a flexible and strategic approach to managing livestock businesses i.e., be willing to routinely reassess where the farm system is at any point.
- Tactical adaptations and diversifying (i.e., spatially, production type, off-farm income) are pathways of change that producers have some capacity to self-direct.
- Greenhouse gas mitigation with carbon farming (sustainable futures pathway) and implementation of technological innovations (transformational pathway) require a collective approach alongside RD&E investment and support services – these pathways are challenging for producers to self-direct.

4.3.1 Producer experiences

Climate related impacts and responses

All interview participants (which included eight producers and one company consultant) mentioned the drought (2013 onwards) and the recent flood event (2019) as being major climate-related events that were disruptive to their livestock businesses. However, because of the variability in the severity of flood impacts (with some producers minimally affected relative to others), some producers focused on the impacts of drought, rather than the flood event. The major impact from the drought was not having the native pastures to support the herd size that was considered viable for their business. Therefore, the response was to destock their property either by selling cattle down the supply chain or moving cattle to family or agistment properties that had enough grass. In some cases, the core herd was kept on the main property where some supplementary feeding was used to maintain the herd. Based on their direct experience with the recent drought event, several producers have changed their joining and calving dates to adjust to new seasonal patterns in anticipation that the wet season is coming later. (Table 15).

In terms of the 2019 flood event, the major impact was losing a significant proportion of the core herd and having damaged native pastures. In some cases, the native pastures did not respond to the follow up rain that occurred, while in other instances this follow-up rain triggered a good response to their native pastures to support some grazing. Where grasses came through, this was considered a 'window of opportunity' to trade cattle to generate some cash flow. Where the grasses did not come through, it was observed that producers transported their herd to other properties further south for agistment or taking up leasing arrangements. Most native pastures were still recovering from both the recent drought and flood events. (Table 15).

Four producers mentioned government funding as providing a 'lifeline' during the drought and flood events, which helped to rebuild the core herd, purchase trade cattle, or invest in improving on-farm infrastructure to build a more resilient production system. Visits from politicians to the drought and flood affected region was also welcomed by one producer as a genuine gesture of support and understanding.

Several producers mentioned combinations of the Live Export Ban of 2011, high real estate values, and other market forces as also significantly disrupting their livestock businesses indicating that adaption to 'shocks' and changes involves responding to a range of events that are both climate-related and market-related (shocks in the broader socio-economic system).

Table 15. Key responses to the recent flood event and drought conditions. Names have been changed.

Short-mid term response to drought/ flood	Destocking	Trading cattle in domestic markets	Altered joining/calving times	Containment/ supplementary feeding	Moving cattle to agistment/other family property	Investing in farm infrastructure	Applied for government disaster relief funding	Rebuilding core herd	Shifting cattle to higher ground	Choosing different cattle breeds	Changing grazing regime
Nathan	Drought	Flood								Flood	
Helen	Drought	Flood	Drought				Flood			Flood	

Craig	Drought			Drought	Drought	Drought	Drought				
Julie	Drought						Flood				
Melinda				Flood	Flood		Flood		Flood		
Alicia			Drought			Drought					Drought
Richard	Drought	Flood		Flood	Drought						
Graham	Drought			Flood				Flood			

What lessons were learned from these recent experiences in adapting?

Most of the interview participants agreed that they had learned a few lessons from their experiences of the recent drought and flood events and their observations of weather patterns. The lessons learned involved:

- Taking a combination of both tactical and strategic actions to adapt e.g., trading cattle and de-stocking as an immediate response.
- Developing a long-term view on pasture management.
- Maintaining the body condition of the herd so that the cattle have a better chance of surviving and performing during and after the drought or flood event.

Embracing a flexible approach to managing both livestock and the business was considered a critical factor by several producers. This meant building a repertoire of alternatives to consider as you go along, which may require elements of experimentation and luck. Sometimes adaptation was framed as a straightforward process of producers applying industry best practices to build their resilience to climate related events. Overall, the producers and consultant assumed that they will be able to continue their red meat production into the foreseeable future. At the same time, several producers mentioned that it was a challenging venture when there is little (or no) opportunity to prepare for an event like the recent flood and avoid its impacts – some things are out of their control.

4.3.2 Producer perspectives on adapting to future climates

The following results are framed in the context of the four future scenarios co-developed during the Nexus project with the reference group members and CSIRO modellers: adaptation, diversification, sustainable futures, and transformation.

Adapt

The suite of options in the adapt pathway are currently being demonstrated in the region to varying degrees by the red meat producers/company consultant interviewed. All interview participants indicated that they were already undertaking at least several (if not all) of the actions listed under the ‘adapt’ pathway. These comments correlate with the descriptions of their responses to the recent drought and flood events in the region. The ‘adapt’ pathway is therefore considered a feasible option by both the reference group producers and those producers who were not part of the reference group.

Prompts/motivating factors

Makes good productivity and business sense to operate along an 'adapt' pathway

When producers were asked what prompts or motivates them to implement these adaptations on their property, it was sometimes about applying industry best practices no matter what the conditions are (e.g., controlled joining, culling of non-productive cows, managing woody thickening). Other times it was about responding to a recent extreme weather event or observing a change in the timing of the seasons over a few years (e.g., reduce breeder herd size to match long-term carrying capacity, calving Jan/Feb) in combination with taking advantage of a fortunate situation (e.g., opportunistic use of trade cattle in good years). The motivation to adopt these practices is that they make logical sense for both productivity and profitability:

> *"So I guess I think they're all very logical things that people should be doing their best to put into practice if they can… those things are all good business decisions to be working towards."* (Richard, Producer Interview, 2022).

Likewise, the 'adapt' pathway for Craig represents a set of proactive practices that are helping to build the family business to support two generations of beef producers (parents and siblings). The original property is no longer managed as a subsistence farm like it was in the 1950s because the livestock enterprise must provide a livelihood for multiple children as part of the family succession process.

Not all Red meat producers in the region are heading down the 'adapt' pathway

Richard stated that the 'adapt' options should not need any encouragement or persuasion because they are simply good livestock management practices, "It's just something that we should be doing even without being prompted," (Richard, Producer Interview, 2021). Following on from this, Richard thought that there is already information and education on these adapt options, and these practices should become common knowledge across the industry. However, some interviewees held the opinion that a large proportion of producers in the region are not adopting these standard good practices, which implies that they are not adapting to the region's changing climate using known tactics:

> *"I couldn't express how important [these adapt actions/options] are, and definitely people do not do them, but we do… all of them. [For example] a lot of people don't control [their] mating so they have cows calving all times of the year. Some of them don't pregnancy test so they don't know what cow is productive and they just carry extra cows that they don't need".* (Helen, Producer Interview, 2021).

Melinda explains the non-adoption of the 'adapt' options can be an indication of a level of complacency among some family-owned livestock businesses (as opposed to corporate pastoral companies) because the demand for red meat is a constant, therefore the red meat producer has an endless market to supply:

> *"[T]here's a fair bit of pushback from some private producers [when it comes to changing their practices]… who are just like, "Whatever, [the human population] always needs protein. I don't have to do anything [different to the way I currently manage my livestock production]""*. (Melinda, Producer Interview, 2021)

At the same time, livestock producer Melinda acknowledges that there are other private producers who are making efforts to demonstrate their efforts as environmentally sustainable and ethically responsible red meat producers.

What enables implementation?

In terms of what can enable the implementation of the ‘adapt’ pathway, there are a combination of factors that were identified by the interviewed producers to support their own situation. At the property level, it is about combining certain biophysical assets (e.g., Open Downs Country for easier livestock management, as opposed to more rugged terrain) and physical assets (e.g., fencing infrastructure to control livestock movements) with skills in monitoring the livestock enterprise (e.g., record keeping of stocking rates and pregnancies).

Interviewed producers also identified factors to support adaptation at a broader industry level. Implementing the actions under the ‘adapt’ pathway can be supported by normalising these actions as an industry standard to overcome a general perception that these actions are unconventional or marginal. Several interviewed producers referred to the inputs of public extension staff or using private sector agricultural advisory services as an integral part of deciding how to adapt their livestock businesses. In one unique case, Graham thought climate change adaptation could be enabled by consumers being prepared to pay higher prices for their meat products to ensure the income of producers is not significantly reduced from carrying less livestock to match the long-term capacity of their native pasture system. Therefore, adapting to an increasingly variable climate is a societal response, not just the responsibility of the producer.

What inhibits implementation?

In terms of what inhibits the implementation of the ‘adapt’ pathway, the interviewed producers tended to identify specific factors that can be difficult for them to control or influence as well as identifying those situations that they considered were beyond their control:

- limited availability of agricultural extension and advisory support services in the region,
- overcoming confidence issues with applying Indigenous knowledge that uses fire to manage native pastures effectively,
- reaching a personal threshold for making or responding to change,
- negotiating changes in practices with parents who were still involved with the family business and who were not convinced of the need to make significant changes (e.g., facing resistance to applying rotational grazing on the property),
- navigating complicated regulations (e.g., vegetation clearance regulations),
- experiencing consecutive poor production seasons (e.g., persistent dry years),
- increasing land values (e.g., making land unaffordable for purchasing additional land to reduce stocking rates).

Some interviewees provided expanded responses for the first three inhibitors for implementing the ‘adapt’ pathway. Helen referred to the historical withdrawal of public agricultural extension by state government departments, which left a significant gap in service provision to livestock producers over decades. It took the recent flood event (2019) and the resulting crisis for the livestock industry to trigger another round of investment in public extension:

> *“There’s been no Department of Agriculture staff for many, many years, except for a small handful…one or two staff have been…expected to service and support all the producers and graziers in [the] area, and they’ve been unable to do that effectively…a lot of grazing and general enterprises not being able to get that access to the resource of information [and] knowledge sharing. So that lack of government resourcing has also led to a breakdown in [producer] relationships with department staff…a lot of people can now go online, but there’s a lot in the generation above that may or may not use that online service. The extension has*

really evolved away from this region, and it's only just recently returned in the last few years since the floods…so that's had a big impact." (Melinda, Producer Interview, 2021).

In reference to adopting new fire regimes to improve pasture management, Melinda describes the unfeasibility of applying Indigegnous fire knowledge as an adaptation in the Southern Gulf region because this knowledge is generally inaccessible, producers lack the confidence in using fire in persistent dry conditions, and there is a general breakdown in the social relationships between Indigenous land managers and non-indigenous livestock producers:

> *"So there's not enough knowledge out there and not enough confidence where people would use [fire] as a tool to manage their pastures and get a good result for it, because they're just so concerned that it won't rain because we are in a really variable climate here. So they don't take [on] that risk, so that risk appetite really has a bit of a role to play there too. There probably is no one else here that has knowledge anymore…that's definitely the case [in another neighbouring region], but that relationship breakdown over the years has led to a lack of trust between the producer and the indigenous ranger program….there's just a whole lot of conflict around that sort of issue up in these parts too, which would prevent a good relationship around that sort of potential tool being used."* (Melinda, Producer Interview, 2021).

Interestingly, one producer interviewee commented that it can sometimes be difficult to pinpoint what leads to adoption of farm practices in general because people have different thresholds for change. The point in which a producer reaches their limits for making change is often not known by the producer or is made explicit by the producer. Then if a threshold has been reached, it is difficult to identify what actions a producers can realistically take, *"[W]hat is their threshold for change and when do they meet it, and then what do they do after they reach that?"* (Melinda, Producer Interview, 2021). One example of having reached a threshold for change is Graham's situation. Graham explained that while his knowledge base to adapt and operate productive red meat businesses was there, the limiting factor for him was coping with the consecutive dry seasons over the past few years. This meant that his actions were orientated towards operational maintenance, rather than adapting to generate improvements and resilience.

> *"Our herd size probably has been reduced out of our control…from the flood event, so we haven't replaced fully because we haven't had the season. The ideas [for maintaining and increasing productivity and profitability] are there but, again, having the season or the feed base to have the right [body condition scoring] to be able to make it work is our challenge. The things that we would love to do…there's a list a mile long, but when you're only…trying to keep things ticking over…we're not able to do [adapt actions] at this stage".* (Graham, Producer Interview, 2021).

This suggests that Graham had reached some sort of limit in his capacities to progress his livestock business under specific and unforeseeable weather conditions that tested his capacity for change.

Table 16. Summary of prompts, enablers and inhibitors for implementing the ‘adapt’ pathway.

Adapt actions	Prompts	Enables implementation	Inhibits implementation
General adapt actions	• Contributes to the profitability of the business • Need to be applying industry best practices to stay in business • Need to manage environmental risk, greenhouse gas mitigation, and animal welfare elements • Investor and social accountability (corporate board decision making and consumer pressure) • Passing on a sustainable livestock business for the succeeding children • Seeking new opportunities beyond livestock production – lifestyle property	• Normalise to make it a basic/common industry practice • Appropriate for land type/biophysical features • Relevant to the individual producer • Access to the “correct” information and knowledge as opposed to a sales pitch or misinformation • Access to DAF extension staff • Using consultants and financial brokers for financial and agricultural advice	• Culture of the family • Not having the fundamental knowledge of livestock production e.g., nutritional fundamentals of the rumen or pasture management • Having consecutive bad seasons/years so that its about maintenance mode, rather than improvement mode • Reaching a threshold for change • Lack of regional service provision e.g., not enough DAF extension staff to deliver information and advice
Controlled mating	• Experiential learning • Practising good livestock management	• Fencing infrastructure • Open Downs country makes it easy to manage bull movements/joining	• Rough and scrubby terrain and large paddocks are difficult to fence hence manage and contain bull movements
Shifting calving dates	• Experiential learning • Practising good livestock management	• Climate apps and observations of shifting seasons	No relevant data captured
Rotational grazing/pasture management	• Practising good land management practice • Investor and social accountability (corporate board decision making and consumer pressure)	• Demonstrate positive impacts in your own production system, as well as ways that overcome the perceived disadvantages	• Farming parents who are not completely convinced of the value of rotational grazing • Perception that it requires more labour units
Matching stocking rate to land capacity over the long term	• Experiential learning • Practising good livestock and land management • Investor and social accountability (corporate board decision making and consumer pressure)	• Consumers to pay more for red meat products to help producers maintain their income while carrying less stock • Long term record keeping and monitoring to calculate the long-term carrying capacity	• High land values mean it is too expensive to purchase or invest in additional land as a strategy to reduce stocking rate
Controlled woody thickening	• Practising good land management for improving the pasture	• Using sheep and goats to graze and control sapling growth	• Poor seasons makes it difficult • Complicated regulations about vegetation clearance

	• Investor and social accountability (corporate board decision making and consumer pressure)		
Trading cattle	• Production benefits: Cash flow opportunity in certain conditions when the season is good with extra grass allows you to maintain a core breeder herd without having to destock in dry years	• Low cattle prices in domestic markets for buying in/poor production conditions interstate relative to the Southern Gulf region • High cattle prices in domestic markets for selling in/good production conditions interstate	No relevant data captured
Culling of non-productive cows	• Production and management benefits	• Fencing infrastructure for controlled joining • Skills in recording keeping and pregnancy testing	No relevant data captured
Improve pasture health	• Experiential learning • Observing Mitchell Grass responses to rain • Gaining the benefits of retaining soil moisture to support herbage growth	• Allowing the seed bank in the soil to develop native legumes, forbes and grasses	• A lost opportunity for native pastures to be regenerated using fire because of a lack of access to Indigenous knowledge, lack of confidence to apply such knowledge and a break down in relationships between Aboriginal rangers and non-aboriginal livestock producers.
Maintaining and improving farm infrastructure	• Production efficiencies	• Co-funded projects between the producer and funding bodies e.g., improving water infrastructure in partnership with regional NRM organisations	No relevant data captured

Diversify

The diversification pathway was generally regarded as an attractive opportunity for spreading climate, financial and market risks. Diversification for one producer is considered essential for buffering and supplementing the income of their livestock business:

> *"There needs to be diversified income because…we're highly subject to beef prices at the moment…we're just highly exposed to it…if the beef price crashes, it [impacts on the the] family business' main income."* (Craig, Producer Interview, 2021).

However, while all producers agreed diversification can be advantageous and enable adaptation, the high real estate values across Australia and poor access to skilled labour in the region were key constraining factors for achieving this pathway.

Prompts/motivating factors

Generating off-farm incomes for financial gain and person satisfaction

The motivating factors for income diversification through off-farm work was both personal (e.g., pursuing a 'passion project' or career ambition) and financial (e.g., growing the family business by investing in equipment for contract work, integrating a son or daughter's non-agricultural business with the livestock enterprise or gaining public service employment to provide a stable income for a growing family).

Spatial diversification to grow the business and manage drought risks

Producers have been and would be prompted to spatially diversify mainly for productivity and profitability gains as well as responding to drought conditions (e.g., having additional land resources for maintaining a stable stocking rate, increasing feed security by producing fodder crops that could be conserved, supplying different cattle markets).

Having different cattle breeds and mixes of livestock species adds flexibility to the business

Breeding and managing different cattle breeds or mixes of livestock (cattle and sheep) can add flexibility to the livestock business by having alternative markets to sell into at different times depending on the season, volatility of market prices and market access (e.g., improving Brahman breeds to increase their general marketability, cross-breeding with Brahmans to gain access to both domestic and live export markets, selling wool if cattle prices drop or live export markets close).

What enables implementation

Diversification of the cattle business was thought to be enabled by any new enterprise or income source aligning with the main business model in terms of skill sets, interests, time resources and financial goals. Diversifying the business should provide the producer with the opportunity to pursue and maintain their enthusiasm for the work they do:

> *"I think that there are lots of options, but it does need to be something that…you're passionate about."* (Alicia, Producer Interview, 2021).

It should also provide profitable outcomes otherwise your motivation for diversifying could be affected:

> *"So, part of that sustainably is [labour] hours, doing activities that have a high or a good economic return so that you don't…lose your passion for what you're doing [livestock production]."* (Craig, Producer Interview, 2021).

In other instances, diversification was thought to be enabled by having the capacity to utilize family labour or deploy labour strategically across the different enterprises or properties without needing to source, train and pay for additional staff.

What inhibits implementation

Livestock producer interviewed frequently mentioned two factors that limit the diversification of their livestock businesses. Firstly, high real estate values across Australia makes acquiring additional land in another more attractive climatic zone less affordable, or in some cases, completely unaffordable. Unaffordability can be related to the fact that agricultural land is valued as an investment based on capital gains, rather than its potential agricultural productivity:

> *"It's really expensive to buy country so that makes that very difficult. Land prices are just crazy at the moment…everywhere…so there's a disproportion between land prices and actual [value]… Agricultural land is being sold for a lot more than it's actually worth in productivity because of capital gains."* (Helen, Livestock Producer, 2021).

Secondly, the producers frequently mentioned that it is difficult to diversify whether that be through off-farm income, mixed enterprises, or spatial diversification because there is poor access to a skilled workforce in the region to support these new activities:

> *"Staff now is an enormous problem in the agricultural industry. We no longer have rural colleges; they've all been shut down. So, to get…young staff, you have to get them from scratch, and you have to train them. And most of them just come for six months, 12 months to have a bit of fun, you put your time and effort into them, and they [leave] – they just have a gap year or something. So, staff is an enormous issue for this industry…to diversify, you [must] have staff – you can't do it all yourself."* (Julie, Producer Interview, 2021).

The workforce issue was related to a general trend of closing regional agricultural education and training facilities that would have otherwise invested public resources in developing a skilled workforce for red meat production. The follow-on effect is that the training responsibility has shifted to the livestock producer requiring them to use their own resources to repeatedly upskill short-term employees or contract workers.

Other inhibiting factors for diversification related to biophysical assets (e.g., specific soil types limiting what pastures can be grown), government regulations (e.g., restrictive water licensing, international trading policies that close down niche markets) and personal factors (e.g., not having the time to focus on multiple enterprises).

Table 17. Summary of prompts, enablers, and inhibitors for implementing the 'diversify' pathway

Diversify action	Prompts	Enables implementation	Inhibits implementation
General diversification	• Good economic return to support the sustainability of the family farm business i.e., long-term profitability • Lower vulnerability to the volatility of beef prices • Making the most of your land resource • Providing opportunities for other people to pursue their agricultural passions through share farming	• Being able to absorb the labour required within the family • High mental and physical capacity to focus on diversifying	• Difficulties with securing skilled agricultural labour to work on remote livestock properties that are not near urban centres or have a critical mass of contractors in the area to attract younger staff • Governments shutting down training facilities for the rural industries – less skilled labour available to support agriculture • Spending additional resources training and managing contract staff
Purchase/lease/agist on additional land outside the region– spatial diversification of livestock business	• Managing climate/drought risks • Common practice to spread production risk e.g., purchasing in the Northern Gulf region to access land with more reliable rainfall for breeding cattle or further south to grow/store feed crops/run livestock where the rain is more reliable, quicker responding soils to rain events and better access to markets • Achieving a consistent stocking rate • Potential to grow the business and supply different livestock markets	• Compatible with your business model including other employment commitments • Lower real estate prices in target areas	• High real estate values across Australia limiting access to land resources • Land values create incentives for people to invest in real estate, not a livestock business • Cannot share overhead costs across multiple properties that are located at a long distance from each other e.g. need a tractor on every property • Need to truck cattle between properties, which is an expense • Land in the Northern Gulf region is tough terrain with phosphorous deficiencies
Off-farm income through other work opportunities	• Steady income stream for bringing up children • Pursuing an additional career (e.g., Vet) • Diversify the income streams of the family business	• Having labour to deploy for maintaining the property (weed management and checking water points) or working machinery for contract work • Employing staff to allow the producer to pursue their passion work	• Trying to do too many things so that nothing is done properly • Having to risk your professional reputation by outsourcing your labour
Financial investments in real-	• Provides a supplementary income	No relevant data captured	• Declining value of commercial buildings • Unreliability of share markets

estate/share markets			
Biodiversity and ecological service markets	• Provides a supplementary income	• Cost-effective provision of biodiversity or ecological services • Accessing more information about these alternative environmental markets	• Reducing the viability of the livestock business if it means locking up productive land • Wildlife and feral animals damaging conservation area •Need to invest in fencing to keep wildlife/feral animals out
Mixed enterprise-sheep, cattle, and goats	• Spreading the risk across multiple commodity markets • Enjoyment from running different livestock enterprises • Sheep and goats to graze out the woody thickening	No relevant data captured	No relevant data captured
Managing different cattle breeds for targeted markets	• Turning off an animal earlier and/or lighter (e.g., Wagyu) for same or more money • Securing access to multiple markets adding flexibility into the system	• Seasonal conditions allowing you to turnoff earlier • Feedlot taking a lighter animal with a little discount.	• International relations and government regulation affecting the viability of international niche markets
Growing forage crops and drying/storing fodder crops	• Feed management strategy to provide feed security in response to droughts/other events	• Purchasing land further south where the grain industry is established with access to skilled contractors • Family member to work the additional feed crops further south • Capacity to trial legumes on main property	• Fodder industry is not established in the Southern Gulf region • Variable rainfall • Soil types – alkaline soils limit the variety of crops that can be grown successfully • Water licensing limits water access and therefore the expansion of irrigation to support business growth
Dry feed business (observation of a local producer taking action)	• Needed an income after losing livestock and infrastructure in the recent flood event (2019) • Supplying hay/silage to fill a regional feed gap caused by recent drought conditions	• Continued demand for dry feed in the region	No relevant data captured

Sustainable futures

Interviewed producers indicated significant interest in the ’sustainable futures’ pathway by mitigating greenhouse gas emissions as well as adapting. While there was generally a strong interest in ’the sustainable futures’ pathway, there were uncertainties and therefore hesitancies with knowing how to implement this pathway. Some of these uncertainties could potentially be overcome by providing more detailed and practical information:

- how to account for carbon in livestock production systems
- identifying what ecological service markets are feasible and available
- investment and access to research that provides evidence for the feasibility of growing biomass (trees or other vegetation types) in the Southern Gulf region
- having a clearer cost:benefit or value proposition for storing and/or trading carbon alongside other actions to transition to carbon neutral production.

Two producers interviewed anticipated that they will need to engage with this pathway as an inevitable outcome of a policy directive from government or industry, as well as needing to respond to increasing public pressure to reduce greenhouse gas emissions. In this context, producers have little agency for deciding to adopt this option or not, because it will become an issue of compliance and as a public relations matter for the red meat industry in Australia.

Prompts/motivating factors

In terms of what would motivate interviewed producers and company consultant to implement actions towards running a ’sustainable futures’ enterprise, the three main prompts were:

1. having another way to improve your production efficiencies by managing your system for increased soil carbon,
2. having no choice but to become carbon neutral as a matter of compliance with regulations or policy directives,
3. a way to maintain their social license to continue red meat production.

Although two producers were resigned to taking action towards carbon neutral agriculture and regarded it as a matter of coercion, one producer commented that it is right thing to happen:

> “*We'll have to do [carbon neutral agriculture] eventually…we'll be forced into doing it…we aren't actually carbon [neutral] at the moment…beef…has got some pressure on it at the moment and I think - it's a good thing - well, if the liberals and nationals can agree to commit to the 2030 carbon neutral goal*.” (Craig, Producer Interview, 2021)

The push towards carbon neutral agriculture within the red meat industry was considered by Nathan to be a positive move for managing the image of the industry, although it would not be a prime factor for adopting this pathway:

> “*I think it’s a good thing for the image [of the red meat industry]…seems to be a pretty strong thing for the consumers to be going towards carbon neutral. I feel they feel it’s a good thing for the industry to do*.” (Nathan, Producer Interview, 20121)

In contrast, while Julie stated she considers climate change as real, it has become a political issue that has resulted in the red meat industry becoming a ‘’soft” target for “hard” policies directed at greenhouse gas mitigation. Julie stated that if you take a cynical perspective to carbon neutral agriculture, livestock producers could be seen as an easy target to blame and apply a regulatory approach to, while other industries with more political power (e.g., mining), will be able to continue to maintain or increase their carbon footprint.

In the case of the pastoral company, the company consultant indicated that while part of the motivation for carbon neutral production was to achieve greater productivity and profitability, an equally important motivator was to respond to the pressures applied by the company's investors to align with societal (consumer) values.

Only one producer interviewed explicitly expressed the need to implement the sustainable futures pathway for mitigating methane emissions.

What enables implementation

The sustainable futures pathway was thought to be enabled by a range of factors that were either general in scope or related to specific actions. In a general sense, the sustainable futures pathway would be more feasible if there was more dedicated and available research that proved there were productivity and environmental benefits or that it would be an expensive investment:

> *"What we would need to take on [carbon neutral agriculture] would be a lot of research, and a lot of guarantees that it's beneficial for both the environment to productivity, to really make it take hold - even if it didn't improve productivity…then it would need to be very cheap and economical to do because people are just not going to pour a heap of money into it if there's no benefit to them in the short term [for example,]if it improves live weight gains basically…you'd want it to be well researched so that that data's out there so people can do the figures and go yeah, okay, well not only are we helping the environment, but it's also helping our bottom dollar." (Helen, Producer Interview, 2021)*

Helen described how she has sought information about soil carbon sequestration with an agronomist through her regional NRM body and was provided with a possible reason why the organic carbon on their property was very low. The reason given was related to soil temperatures and carbon oxidising which released carbon dioxide to the atmosphere. Helen's reaction to this new information was uncertainty about what the potential her property had to sequester carbon and signalled that she would like to be guided by expert advice:

> *"I'm not an expert, I have really very little knowledge about it all. I'm not really sure…I'd like to see some experts tell me what to do. I'd happily uptake that if there was good clear evidence to show how we could sequester carbon into our soils."* (Helen, Producer Interviews, 2021).

Graham regarded climate change and other environmental issues as a shared problem where the costs for adaptation and mitigation should be distributed more widely across society, for example to include urban consumers. Graham refers to examples of visiting cities where lights are left on in buildings all day and night and where good agricultural land located close to city centres that could be used to produce agricultural products with low food miles, are instead developed for residential housing and forcing agriculture to take place in more marginal landscapes. Therefore, urban communities are part of creating the problem.

Yet Graham is of the belief that consumers who largely live in urban centres see climate change and other environmental issues as, "the farmer's problem or…a rural problem" (Graham, Producer Interview, 2021). Graham would ideally like the expense of transitioning to a sustainable futures pathway to be a shared cost with consumers paying a premium price for red meat products produced with a low carbon footprint.

"How we get the whole population to understand that it's a whole population issue, and if you aren't in a position to change it yourself, then you need to essentially pay somebody else to change it for you." (Graham, Producer Interview, 2021)

This would demonstrate that urban consumers are taking responsibility for the climate change problem. Producers taking action on sequestering carbon in soils would be enabled by knowing their current carbon levels to establish their baseline, having more research activities conducted in the Southern Gulf Region to provide relevant information about what can be done with the soil types in the region matched with what grazing regimes, and a focus on how legumes can contribute to soil carbon sequestration during low rainfall conditions.

Producers choosing to use feed supplements to reduce methane emissions from livestock would be enabled by administering the supplement through their watering points, having research to reassure producers that if the supplement is administered via a bolus there will be no negative impacts on the digestive health of the animal, having supplements subsidized or provide a good return on investment such as providing an integrated solution for turning off livestock earlier based on improved growth rates.

In the case of the pastoral company, the company consultant indicated how the economies of scale (multiple, large properties with big cattle herds) and access to resources (operating as a team of managers and employees with access to investor funds) allows the company to initiate new projects and lead their own innovation:

"So [the pastoral company has] already got their own emissions trading herd [management] methodology… basically it's a project initiated by [the pastoral company] themselves, so they've already jumped in front there of everybody else, and been quite proactive." (Melinda, Producer Interview, 2021)

What inhibits implementation

Producers indicated that the transition to the sustainable futures pathway was hindered by not having a clear understanding of what the pathway and actions involve at the practical level. Other barriers include the requirement for farm labour and time resources to be used to achieve carbon neutral production, the cost of soil carbon testing and the complexity with establishing a baseline for your carbon accounting. Sequestering carbon by increasing biomass on the property was considered a risky option if it means growing trees in paddocks that are required to be 'locked-up' and taken out of the production system. There was also uncertainty about what legal obligations a producer would need to uphold under carbon credit agreements and how your carbon credits would be affected in the event of a bushfire. One producer described how soil carbon sequestration rates would be negatively impacted by persistent low rainfall, suggesting it is not always feasible to achieve soil carbon sequestration in certain weather conditions.

In terms of reaching a threshold for change, one producer explained how a consultant has calculated his cattle operation as a generator of carbon credits from turning of cattle at a younger age. However, these credits are thought to be redundant because he will not be able to demonstrate a further reduction in GHG emissions avoided in the future. This producer concluded that they had already reached an endpoint along the sustainable futures pathway because of the way the carbon credit market is structured. Organisational structures in this example are therefore limiting the adaptive capacity of livestock producers and rewarding adaptation and mitigation production practices.

Table 18. Summary of prompts, enablers and inhibitors for implementing the 'towards carbon neutral' pathway

Toward carbon neutral actions	Prompts for implementation	Enables implementation	Inhibits implementation
General	• Maintaining the social license to continue red meat production driven by consumer values and market demand • Proactive approach to responding to climate change by implementing own carbon emissions strategy voluntarily based on accountability to investor board and consumers. • Forced change – therefore producer will have no choice • In the long term, it will be a new policy setting directing the red meat industry to be carbon neutral • Another potential way to improve business performance and production efficiencies • Legitimizing the cattle industry to the public – good for public relations • Personal interest in the topic area	• Consumers to share the cost of transitioning towards carbon neutral by paying premium price for red meat products that had a low carbon footprint • Economies of scale - having large cattle numbers across multiple properties for demonstrating significant greenhouse gas reductions and carbon sequestration • Needs research to demonstrate that there are both environmental and productivity benefits from adopting these actions • For corporate operations – working with industry partners for support and resourcing • More education about carbon neutral agriculture to be delivered by regional NRM organisations and MLA.	• Not having a clear understanding of what this pathway entails at the farm management level • Requiring more farm labour and time resources
Soil carbon sequestration	• Red meat industry should be aiming to mitigate greenhouse gas emissions through soil carbon sequestration programs • Improving soil and pasture health.	• Establishing a baseline of how much carbon is currently being held in soils at the property level – understanding your starting point • MLA needs dedicated scientists to do confirm that red meat producers have the capability to sequester soil carbon in livestock production to protect the industry's public image • Investing in local research that investigates the potential of carbon sequestration based on the soil types in the Southern Gulf region (Downs Country) and grazing management regimes – different soils hold different capacities for sequestering soils so you need	• Financial cost of accounting for your soil carbon and establishing a baseline for corporate or large sized properties • Difficulty with measuring carbon in soils/farming systems • Lower rainfall will negatively impact carbon sequestration rates

		regionally specific research, research from other regions does not necessarily apply to the Southern Gulf region. • More advice and research into growing legumes in this region with variable rainfall patterns	
Greenhouse gas mitigation (methane) through feed supplements/ additives	• Methane reduction is going to be critical in the future • Productivity and profitability gains with a reduction in greenhouse gas emissions – a "silver bullet" combination	• Option to administer seaweed extract to mitigate methane via watering points (troughs), already administering minerals this way so requires minimal practice change • Cost effective products or could be subsidized by government • Accessing solid research about the impacts on animal health and digestion from using a bolus to administer methane reducing agents. • Currently we are basing assumptions about the red meat industry on outdated science, therefore we need new robust studies around greenhouse gas emissions/mitigation to quantitatively provide the actual greenhouse gas emission contributions in relation to other agricultural industries and non-agricultural sectors to get some perspective on the greenhouse gas emissions the red meat sector generates • Supplement feeding and improved genetics to quicken the rate of weight gain of individual animals for turning off cattle earlier	• Already reached carbon neutral with the management of Wagyu cattle, therefore already at this point so there will be no future credit to accumulate. • Seaweed supplement needs to be ingested everyday therefore impractical
Renewable energy production	• Provides a supplementary income	No relevant data captured	• Property is not located near transmission lines to contribute to the power grid
Growing biomass/trees for	• Provides a supplementary income	• Need more research-based evidence to show the feasibility and cost:benefit of growing biomass (trees) in the Southern Gulf region	• Not having the right land profile for growing trees e.g., Mitchell Grass Downs

sequestering carbon/earning carbon credits for trading		• Pastoral companies already earning an income from generating and trading carbon credits can provide a working example to other producers in the region • Over-grazed country would benefit from being rested and locked-up for growing back biomass/restoring soil carbon	• Having to convert well responding paddocks to non-grazing areas for growing and managing biomass for carbon credits • Uncertainty with the obligations a producer has under a carbon credit contract – if you have a bushfire, does that you lose your carbon credits and be penalised? What happens if you cannot increase carbon storage during drought periods? • Uncertainty of what is the best program to participate in for carbon credits and trading on the carbon market

Transformational

Overall, the producers and company consultant indicated a strong interest in new technologies and innovations to help them adapt to climate change and increase their productivity and profitability. Some producers were already experimenting with drones, automated weighing and water monitoring (agtech), trialling different fodder crops (introducing legumes or new cultivars) and involved in animal genetics (improving cattle breeds). Therefore, the interviewed producers and company consultant were already learning and building their experience with specific technological innovations.

While new technologies and other innovations held strong appeal through curiosity and early-stage experiences, some producers also indicated that they were taking a cautious approach to capitalising from agtech and other innovations. This was frequently due to:

- needing a stronger value proposition (proof) of functionality and reliability, to fully invest in new tools and products
- not wanting to become distracted by the latest gadgets, which may disrupt them from getting on with their everyday production and applying their own low tech or conventional technological practices.

What became apparent is that adopting new technologies and innovations requires support beyond the individual producer's interest and willingness to trial new things – adoption of digital technologies needs regional investment in ICT infrastructure, additional research initiatives in the form of research stations locally embedded for ongoing activities and development, subsidized trials at the property level and general extension services for facilitating the implementation of technological innovations.

Prompts/motivating factors

The producers and company consultant were motivated to consider innovations from R&D if they provided more convenient ways to operate their production systems, reduce labour costs, add efficiencies to their livestock and business management practices by saving on time or use of expensive alternatives, enable better decisions based on the collection and interpretation of precise information of their property and would provide a means to adapt to climate change. For Alicia, satellite imagery would transform her way of making strategic decisions around pasture budgeting:

> *"I think that [satellite imagery] will be a big game changer. There's so much variability just within paddocks…I really struggle with pasture budgeting in that regard. When you've got areas [in a range of conditions] trying to [evaluate your pasture with] so much variation within a paddock [becomes a real] battle to do pasture budgets. We try and make decisions around I guess long-term caring capacity and what rainfall we've had that year [based on] a bit of [a] gut feel… which when you're the new generation coming in, you haven't got 30 years of gut feel to go by…I think that the Cibo Labs stuff will absolutely be able to just help have a bit more objectivity to pasture budgeting." (Alicia, Producer interview, 2021).*

What enables implementation

Adoption of innovative products and practices was thought to be enabled by access to both quality and trusted research that was conducted in the region to make an informed decision about investing and implementing new products and practices. However, this individual decision to purchase and use new technologies or innovations requires a collective effort from public organisations (e.g.

governments, NRM bodies and research institutions), industry organisations (e.g. MLA) and private companies (agtech service providers) to make this individual decision possible:

> *"You need people all along the supply chain both supplying products and services as well as the other end, buying sheep and beef and wool and so on. We're [producer] just part of the supply chain, really." (Alicia, Producer Interview, 2021).*

What inhibits implementation

Decisions to invest and implement innovative products and practices was thought to be inhibited by not having regional scale infrastructure (e.g. digital infrastructure) to support the use of digital technologies. However, one producer provided an example of a local council investigating solutions to this issue. Water regulations (licensing) and lack of irrigation infrastructure were also mentioned as inhibiting the production of fodder crops and other feed conservation measures that would enable adaptation. There was also strong focus on increasing the R&D activity in the region by organisations (e.g., CSIRO) with a long track record and capacity for quality research. Furthermore, it was thought that there was not a strong signal that agtech products generate mid-to-long term value for producers– therefore it is a matter of producing more scientific evidence and having more practical demonstrations of implementing technologies in red meat production to support an innovation adoption decision.

Table 19. Summary of prompts, enablers and inhibitors for implementing the 'transformational' pathway

Toward transformational actions	Prompts for implementation	Enables implementation	Inhibits implementation
General	• Provides a clear cost:benefit • Being able to see the application potential for your own production situation • Adopting technologies that improve the efficiencies in using natural resources, maintaining animal welfare and providing safe working conditions strengthens your social license to operate • Enjoyment from experimenting with novel technologies and discovering new opportunities for the production system/business • Making life easier and improving the efficiency of the red meat production • Organisations like AgForce are conducting property mapping to monitor weed management – map shows accurate paddock sizes for planning infrastructure and can be used as a reference to help new staff navigate their way around the property - assisting with managing OHS issues.	• New technologies such as remote water monitoring and automated weighing are considered feasible and available now • Technologies that are backed by quality research • Pastoral companies and or producers who belong to regional catchment groups have got the economies of scale and resources to trial and implement new ideas – this comes with having financial resources/funding to host researchers to conduct trials on properties and monitor the research/take samples etc. • Having a way to sort through all the tools and easily assess the value proposition of each i.e., working out what will help • Example project mentioned: E-Beef Project that demonstrates the latest technologies for improving productivity. Smart Farming technologies that are demonstrated include: remote walk-over weighing unit with auto draft, satellite monitoring and an online benchmarking program, to provide producers with almost real-time data to make earlier critical grazing management decisions and forward plan impacts on profitability. The E-Beef project is supported by a partnership comprising Southern Gulf NRM, Desert Channels Queensland, Northern	• Not having mobile reception and relying on satellite coverage • Agtech could be an investment risk that might provide interesting data, but not useful data for improving productivity and include hidden costs such as yearly subscriptions to access your data and installation costs • Short political cycles (every 3 years) means changes in policies and funding, which does not provide a stable, supportive environment for long term planning of the family business • Technologies can be unreliable by breaking down and this erodes trust in using new technologies • Opinion that many producers in the region are not motivated to try new innovations because they do not want to change – they are happy with the way they have always done things (including younger aged producers). • Lack of quality and independent information about new innovations and technologies - which is where government and industry support groups have a role to play in making sure that the right information is provided, rather than a sales pitch from a retailer.

		Gulf RMG, and Queensland Department of Agriculture and Fisheries. • Subsidized trials for experimenting with new technologies on your own property for a period of time • Producer demonstration site model • Having early adopters in the region give new technologies a go, and then sharing their success stories to their neighbours/peers – the value of adopting new innovations is likely to trickle down to other producers. • Regional research properties with investment in regional R&D projects -to provide learning opportunities for the red meat industry • High-speed internet and infrastructure to support wireless connection – the local shire is investigating options for developing the digital infrastructure of the region – this would incentivise producers to consider using remote sensory technology, for example: soil moisture probes, trough monitoring, soil profile measurements etc. This will allow for Big Data driven decision making from the convenience of a laptop, iPad or mobile phone. • Currently you can buy a Telstra small cell to give you mobile coverage at that spot • Long term investment for regional R&D – CSIRO could set up a trial property to test how native grasses/fodder crops respond to high temperatures (45 degrees), the results of the trial site could be useful for producers in southern Queensland and parts of NSW because the current conditions of the	

		Southern Gulf Region may be a proxy for their future climate	
Satellite imagery	• Improvements in pasture biomass measurements via satellite imagery that are accurate and regular, which helps with pasture utilization budgets. • Potential to be integrated as part of a manager's tool kit	• Precision agricultural services are now available - Cibo Labs PastureKey service (in partnership with MLA) provide satellite assisted estimates of pasture biomass and ground cover for weekly forage budgeting and land condition monitoring. • Pastoral companies and producers are doing their own ground truthing of the satellite imagery to test the accuracy - improvements in the accuracy have been made based on the data being collected out in the field.	• The reliability of the imagery is not there yet.
Drones	• Good to be used for a quick overview or check in of your paddock and livestock • Saving on labour costs and reduces need for skilled labour for certain tasks (e.g., monitoring of fences or livestock) • Assist with estimating available pasture from various points of your property – a visual estimate from wherever you are positioned would be helpful. • Tool for weed control - to drop “pellets” on prickly acacia at the right time using a drone would avoid time and kilometres spent on the motorbike or avoid expensive use of helicopters	• Having other local producer being prepared to test and trial drone technology on their own properties .e.g., use of drones for mustering sheep	No relevant data captured
Remote sensing technology	• Reduce the need for labour for monitoring	• Having public organisations (e.g., regional NRM bodes) fund comprehensive projects. • You need 110% reliability on sensory technologies for remote water monitoring otherwise they aren't useful. • As phone services advance, this could be a real option	• Unreliability of these technologies e.g., satellite rain gauge that needs replacing • Analogue rain gauge is still here as a back-up • Automating monitoring is risky because it can malfunction so prefer to drive around property to check grass, cattle and water for 100% assurance that everything is ok

			• You need 110% reliability on sensory technologies like remote water monitoring otherwise they aren't useful
Improvements in climate forecasting	• Accessing the 2-year forecasts is very useful for planning your musters or livestock branding tasks	No relevant data captured	No relevant data captured
Animal and plant genetics (genomics)	• Animal genomics is big business and potential buyers now require a piece of paper to prove the DNA/genomics of each animal • Potential to help with reducing the heat stress in livestock with genomics	• Need more scientific evidence to support that genomics can increase the health tolerance in individual animals • Further development of fertility genetic research holds great potential	• Not enough investment in this type of research in animal and plant genomics for northern Queensland, and there is a lack of professional research capacity to support any research investment • Not enough genomic information is being generated to advance "growth" genetics – this the algorithms cannot work with any accuracy – not enough people reporting and adding to the data base • Need to work with native pastures before we introduce new cultivars on a large scale – precautionary approach • Aggressive marketing of cattle breeds e.g., Angus over Brahmans is not based on good scientific knowledge – Angus are not suited to hot, tropical conditions and can suffer heat stress and lose condition easily, whereas Brahmans are a better suited breed for the region
Automated monitoring of cattle movements (ear tag or virtual herding technology)	• Monitor the movements of (high value/long-term) bulls to understand their habits and behaviours over time	No relevant data captured	• GPS technology for livestock is too expensive • Producers are still not comfortable with this technology

Different fodder crops /dry matter/feed conservation **Water infrastructure**	• Curious about establishing legumes or sorghum with native pastures to maintain ground cover during hot, dry periods • Growing fodder crops/storing silage as feed conservation provides feedbase and nutrition security, which assists with maintaining the health of your herd during dry periods • Being able to use any saved water from capping bores/turkey's nests for growing fodder crops as feed conservation	• Would consider growing fodder crops if there was a greater guarantee of water access to (e.g., artesian basin using pivot irrigation system) • Having a water right as a landowner with a registered artesian bore would provide water security and a drought mitigation solution e.g., water licenses permitting 200 megalitres per annum to irrigate 20-40 ha • If producers in a district were prepared to take collective action, then the economies of scale would start to become relevant – if every property offered a 40ha block to be used for a fodder crop then there would be enough work for specialised contractors to use a centre pivot and manage the crop. • Conducting and continuing legume trials as a small trial before scaling it up	• Being prepared to trial fodder crops as an expense, to have them fail two years in a row due to low rainfall • The bulk of the artesian bores now are for stock and domestic use only – not irrigation of crops • Cotton industry monopolize the use of any opportunities for using bulk water and irrigated agriculture • Becoming distracted with trying new things for the sake of it when it is just a matter of managing native pastures that are naturally adapted to the local climate
Walk Over Weighing	• Convenient way to accurately monitor weight gain of individual animals and saves time between deciding to sell and organising transport – could even be just 2 days before organise trucking • Because you can get a good indication of weight gain on a daily basis of individual animals and when weight gain has stopped – you can then decide to introduce supplement feeding to maintain body condition • Reducing the risk of weight loss and injury from unnecessary mustering	• Having neighbouring producers trial and implement this technology on their own properties so that others can learn from these hands-on experiences and decide its practical value	• Need reliable internet connectivity

4.3.3 Examples of adaptive capacities

This section provides a sample of key examples that illustrate the adaptive capacity of the producers and company consultant interviewed. This table does not represent a full inventory of the adaptive capacities of the producers and company consultant as the interviews were not used as a survey tool to compile a comprehensive set of adaptative capacities. The interview material did, however, capture descriptive examples of adaptive capacity as conceptualised by Barnes et al., (2020) to include the domains of agency, assets, flexibility, learning, social organisation and beliefs. These adaptive capacities are likely to influence how producers access, mobilise and use resources for adaptation and change on their property.

This is based on the lived experiences of the producers and company consultant during the recent drought and flood events, as well as their perspectives on the four pathways for change from the NEXUS project (see Table 20 for a list of demonstrated and potential adaptive capacities per domain).

Based on Table 20 which lists demonstrated and potential adaptive capacities of the interviewed producers and company consultant, there are two key themes to draw out: 1. producers have sufficient adaptive capacity when they are in position to self-direct their adaptation in situations that are in their immediate control, and 2. Producers have limited adaptive capacity when they consider their situation outside of their control or comfort zone that entails a moving beyond the tactical, and into the strategic or technologically innovative space . .

Producers demonstrate self-directed adaptation and change for factors that are considered in the immediate control

There is a strong indication that the producers and company consultant have been and continue to be willing to learn new adaptation practices based on their experiences with extreme weather events and weather observations over the past 10 years, which demonstrates life-long experiential learning. The producers have drawn on their own financial resources, funding opportunities and government payments for upgrading property infrastructure (assets). This demonstrates a significant capacity for making incremental and tactical changes to improve their livestock management and business based on their motivation for continuous improvement coupled with a strong sense of personal power to make these changes, being flexible with their management decisions and seeing options as they emerge (agency and flexibility). Producers and the company consultant also illustrated their capacity to socially organise through working with siblings in business partnerships, involving themselves in research and extension activities, seeking funding and government payments when they are made available and self-organising for peer-to-peer learning (organisational capital and social learning).

A range of principles and mindsets were captured that are likely to influence the producer's own motivations and agency for adaptation and change and may reflect their recent experiences of the recent flood event and persistent dry conditions (socio-cognitive constructs):

- operating conditions are always changing (flexible approach to livestock management and planning)
- risk management is key (reducing impacts of weather events and volatile cattle markets)
- need to work with nature, not against it (accepting the biophysical limitations of your property and variable weather conditions)
- belief in personal resilience (need to act early when responding to disruptive situations)

- self-assured in abilities to adapt to climate change contingent on external resourcing (adaptation is in the control of the producer which is enabled by 'neutral' resourcing i.e., policies and funding that support the needs of the producer, rather than a top-down intervention)
- livestock production is not easy and there are limits to how much you can adapt (exhausted options for the moment)
- many producers in the region are not adapting, at the same time extreme weather events can be disruptive (strategies needed to encourage more producers to start on an adapt pathway, while acknowledging the enormity of impacts from the recent flood event)

Supported change is needed for pathways that are considered out of their control or comfort zone

While the producers and company consultant have clearly demonstrated their adaptive capacity for responding to extreme weather events while continuing to build profitable businesses, this does not mean there is limitless capacity for making changes. Transitioning and running a sustainable futures livestock system while transforming through the adoption of technological innovations and implementing new practices requires a collective and shared response from the public, industry, and private sectors (organisational capital and social networks). By providing the programs and projects to strengthen the regional agricultural knowledge system, build capacity for research and experimentation, and enhance networks of infrastructure, then the risks and impracticalities posed by other options for adaptation can begin to be addressed. Transforming red meat production systems is a bigger issue than the producers' individual interests and capacities to adapt and adopt.

Table 20. Key examples of the adaptive capacity of the interviewed livestock producers based on past action and future intentions.

Domains of adaptive capacity	Demonstrated adaptive capacity – recent past	Potential adaptive capacity – future
Agency	• Already adapting, diversifying, and in some cases moving towards carbon neutral agriculture • In recovery mode from recent flood event • Takes a planning approach to livestock management • Identifying new opportunities for the livestock business. • Proactive in utilizing government disaster packages. • Self-directed action that is supported or enabled by providing 'neutral' resources (e.g., government funds that can be used at the discretion of the producer) • Opinion leader • Active facilitator of practice change • Self-determined action/response • Somewhat complex because Helen combines her agency with an element of 'luck' or chance that sits outside of her realm of agency • Identifying the elements that can be controlled	• Choosing not to fully adopt any new technologies at this stage • Resigned to engage with carbon neutral agriculture • Capacity to experiment with feed supplements on property

	• Introducing rotational grazing to family farm • Self-determined action with limitations - can control things up to a point and then other factors come into play that are out of your control.	
Assets	• Secure supply of cattle from sibling's breeding enterprise • Owns a livestock transport truck • Integrated family business that has two properties in different areas • Upgraded water and fencing infrastructure • Financial resources • Core breeding herd • Two properties / land resources • Human resources • Storage sheds, conserved fodder	• Looking to purchase an additional property • Seeking access to skilled farm labour
Flexibility	• Flexible approach to managing the livestock business, E.g., Selling cattle earlier than expected • Adjust herd and livestock business to supply different markets • Adjusting stocking rates/herding numbers in relation to highly variable carrying capacity • Diversifying income streams • Decided to delay the joining dates for cattle • Shifted the Green Date for their local context • Changing the focus from breeding to backgrounding	• Willingness to continue to consider different options in each production cycle – (season/year) • Routinely reassessing production risks and not making assumptions that previous actions will be fit for purpose for the future
Learning	• Experiential learning/direct observations of drought and flood events • Experimenting with trading cattle • Participant in livestock extension programs. • Using climate app to calculate new Green Date • Risk management skills and action can assist with building resilience • Past experiences do not necessarily help for responding to future climate-related events. • Regional weather is highly variable with a range of extremes • Good practice to conserve fodder	• Interested in learning about carbon neutral agriculture • Seeking new information about soil carbon and carbon sequestration • Experimentation with drones • Limited adaptive capacity - may have reached a temporary limit to adapting, diversifying, and learning about carbon neutral agriculture at this point in time
Organisation	• Partnering with sibling's livestock business that is located in another area and functions as an integrated venture • Active participant in research projects and industry programs • Integrating livestock business with daughter's farm accommodation enterprise	• Requesting more formal organisation to provide advice on carbon neutral agriculture • Engaging with regional NRM bodies online through webinars and connecting to agronomists • Involved with satellite mapping through the Cibo Lab project

	• Operate family farm between partner and parents (2 generations) • Accessing support packages for disaster relief • Peer network for seeking production advice • Active participants/leader in pasture management • Arrangements for securing agistment services and leasing land	
Socio-cognitive constructs	• <u>Operating conditions are always changing</u> - believes in a general rule that you need to adopt a flexible approach and be willing to modify plans constantly • <u>Risk management is key</u> – it is challenging to predict the immediate future because of the volatility involved in terms of commodity prices, land values and weather/climate and the threats they pose to your livestock business. • <u>Self-assured in abilities to adapt to climate change contingent on external resourcing</u>– acknowledges that the climate is changing with confidence to direct own gradual adaptation if resourced appropriately by government and industry (financial funds and R&D investment) • <u>Belief in personal resilience</u> - need to keep moving and making decisions about the livestock business regardless of the situation you are in • <u>Need to think about adaptation over time</u> – believes you need to take a long-term view to understand the effects of taking adaptive action on the property. • <u>Majority of producers in the region are not adapting</u> - this may be due to a lack of skills in making strategic and tactical decision for both livestock production and the business and an attitude of resignation that no preparation could avoid the impacts of a flood event of 2019. • <u>Extreme weather events can be disruptive</u> - acknowledgement that there are also limits to responding to extreme weather events when they happen suddenly with unexpected intensity. • <u>Limits to how much you can adapt</u> - weather is a significant variable that you cannot control in livestock production. Uncertain about building up the herd to pre-flood levels because of the unreliability of having good wet seasons. • <u>Livestock production is not easy</u>: the recent extreme weather events have	• <u>Carbon neutral agriculture is good for public relations</u> - understands the industry's motivation to achieve carbon neutral red meat production • <u>Unsure about how to convert a sustainable futures pathway into a practical strategy</u> – not enough information, evidence or advice about integrating this pathway into the business • <u>Need to work with nature</u> - preference for working with current mix of native pastures, rather than introducing new species • <u>Not convinced we are in a climate crisis</u> – does not believe we have reached a crisis point in the last 10 years considering the climate has been hot for a century.

	highlighted that livestock production is a challenging venture. • Need to work with nature – need to identify your property's natural assets and accept the variability in weather and work with the strengths of your "country".	

4.3.4 Prospective pathways for delivering required industry skills, capacities, and capabilities to facilitate industry adaptation

Based on the eight interviews with a range of producers in terms of age, gender and business models including one company consultant, it is likely that there would be benefits to segmenting the red meat producers in the Southern Gulf region to some extent in acknowledgement that producers will have different starting points for adapting, with different capacities for change. Initially it would be about defining their interests and designing activities that allow their interests to be pursued while integrating adaptive actions that are well established or need greater producer involvement to progress knowledge and practices.

Potential segmentation of the red meat producer population in the Southern Gulf Region to support adaptation and mitigation:

- Targeting those producers at the start of taking a journey towards an adapt pathway by matching them with current extension programs and advisory services
- Targeting those that are already along a course of adaptation (which may include some diversification) with an interest in: what else? What's next? - need to establish a collaborative inquiry approach that connects producers, lead organisations, researchers as farmer action groups, Communities of Practice or Living Labs to experiment and demonstrate new practices to support the sustainable futures and transformational pathways
- Purposely working with pastoral companies/corporate livestock businesses by forming industry and business sector partnerships to co-fund co-innovation projects to generate industry goods (based on the understanding that the larger operations can take on higher levels of risk and take advantage of economies of scale)

5 Conclusion

5.1 Key findings

- While average temperatures and the intensity of extreme weather events are likely to increase into the future, inter-annual variability in rainfall will remain one of the biggest climate challenge facing producers in the Northern Downs region.
- Many producers have lived experience of climate-related challenges that they can draw on, but it is difficult to plan for and adapt to extreme events such as the widespread flooding in 2019.
- Without changes to management, the productivity (kg liveweight sold) and profitability of northern beef enterprises will decrease to 2050, and the frequency of years without a profit will increase.
- Of the interventions evaluated, improving the feedbase by oversowing legumes and converting from a breeding herd to a steer turnover operation provided the greatest benefits to productivity and profitability. However, these activities cannot fully mitigate the challenge of operating in a variable climate.
- Continued research is required to identify and develop resilient pasture species that can persist in the Northern Downs region.
- Greenhouse gas emissions can be substantially reduced by changing from a breeding herd to a steer turnover operation, or through the provision of methane-inhibiting compounds (e.g., using an intra-ruminal bolus). However, there are currently limited activities and technologies available to cattle producers and land managers in the Northern Downs region that will substantially decrease greenhouse gas emissions or sequester carbon to offset emissions.

5.2 Benefits to industry

This case study analysis quantifies possible reductions in productivity, profitability, and sustainability of red meat production in the Northern Downs region under future climate scenarios and evaluates the effectiveness of potential adaptation options. Importantly, it also highlights the scarcity of locally appropriate options for climate adaptation, greenhouse gas mitigation, and enterprise diversification in this region. Recommendations are made in section 6 regarding support for producers and future research, which could be used to inform future investment by MLA, or the industry more broadly.

Results from this analysis need to be considered in a broader industry context. For example, at the enterprise level, changing from a breeding herd to steer turnover operation provided the greatest increase in profitability and decrease in greenhouse gas emissions of the activities evaluated. However, our analysis does not consider where calves would be produced instead, and any wider economic and environmental impacts of such a change.

In the context of the broader Nexus project, this research emphasizes differences in climate challenges and the range of potential adaptation and mitigation responses across a transect of red meat enterprises. There are potential cross case-study learnings, with producers in northern Australia already managing conditions that may challenge southern systems under future climates.

6 Future research and recommendations

Improving the feedbase by increasing the quality and availability of feed has potential to transform the northern beef industry – increasing the productivity, profitability, and sustainability of beef enterprises. Required are pasture species that are tough, establish quickly, are resistant to pests, and are capable of dormancy in unfavourable conditions. This could include novel species, or selective breeding and development of existing well-adapted species. Producers also need practical establishment methods suitable for extensive grazing systems (e.g., faecal seeding) and low-risk ways to evaluate the suitability of new pasture species for their property (e.g., local demonstration sites).

Recommendation #1. There is a need for continued research and development into pasture species that will persist in a variable climate.

The frequency and intensity of extreme events is expected to increase to 2050, but this could not be captured in our modelling. Most of the producers interviewed stated that while adaptive management can be used to remain viable in a variable climate, it is difficult to plan for extreme events such as the 2019 floods. The impacts of these events are widespread, impacting infrastructure and supply chains as well as livestock and the feedbase. Producers would benefit from a greater understanding of how to make their businesses more resilient to these events, and how to recover. This could include infrastructure mapping (for insurance purposes), better support for seasonal forecasting tools, training around business and financial management, and access to seed resources to re-sow pastures.

Recommendation #2. Future research on climate adaptation in this region includes a focus on extreme events as well inter-annual variability. In particular, research is required to understand how extreme events such as flooding impact pastures, and how to support the recovery of landscapes that have been inundated for long periods.

Encroachment and thickening of woody vegetation were continually highlighted as one of the main challenges facing producers. Increases in woody vegetation threaten high-value natural grasslands, reduce carrying capacity, and decrease property values. The productivity and economic impacts of this may have been underestimated in our modelling. As part of a toolkit for better management of woody weeds, producers need support to map current and historical woody vegetation cover, and more efficient control options (e.g., biocontrol, use of drones for monitoring and precision application of herbicide).

Recommendation #3. There is continued research into novel and less labour-intensive methods to control woody weeds.

Current heat-stress research focuses on intensive and southern systems such as feedlots and dairy cattle, but tropically adapted cattle in extensive grazing systems may also be impacted as the frequency and intensity of heatwave events increases into the future. An improved understanding of how heat stress impacts production, survival and epigenetics of cattle in northern systems is required. Similarly, there is also a lack of research to evaluate options to mitigate heat stress (e.g., genetics, provision of artificial shade, changes in timing of animal husbandry and management activities) in extensive grazing systems, and trade-offs between climate-smart genetics and market requirements.

Recommendation #4. Research into the impacts and mitigation of extreme temperatures is expanded to specifically target extensive grazing systems of northern Australia.

There is increasing pressure on producers to reduce greenhouse gas emissions from grazing systems, but few locally appropriate options for northern beef systems.

Recommendation #5. Research and development are targeted towards developing options to decrease emissions and sequester carbon in extensive grazing systems. This should be accompanied by clear, evidenced-based guidelines for producers.

Other research, development and extension issues raised by the reference group and interviewees include the need for:

- Greater access to extension staff and advisors. Industry interviews indicated that there are a small number of staff servicing large regions, with high turnover.
- Improved digital infrastructure and connectivity. This could facilitate learning opportunities as well as uptake of digital tools (e.g., remote sensing of feedbase).
- Broader societal recognition of the value of grassland ecosystems.
- Software suitable for individual businesses to test scenarios, and support for producers to do this.

The project research team also suggest investment in larger scale (region or supply chain) modelling of climate change impacts on beef production (e.g., through partial equilibrium modelling). Prices of cattle sold and purchased in northern Queensland are driven by climate impacts in other regions, and options to move stock to another property are based on seasonal conditions in that location. These complexities cannot be evaluated by just focusing on farm-level scenarios.

7 References

Agrimix (2023) 'Progardes® Desmanthus Establishment Guide' Available at https://www.agrimix.com.au/establishment-guide/ [accessed September 2023]

Allen DE, Pringle MJ, Bray S, Hall TJ, O'Reagain PO, Phelps D, Cobon DH, Bloesch PM, Dalal RC (2013) What determines soil organic carbon stocks in the grazing lands of north-eastern Australia? *Soil Research* **51**(8), 695-706.

ANU (2020) 'Tree Change.' Available at http://www.wenfo.org/tree/ [accessed November 2020]

Archer SR, Andersen EM, Predick KI, Schwinning S, Steidl RJ, Woods SR (2017) Woody Plant Encroachment: Causes and Consequences. In 'Rangeland Systems: Processes, Management and Challenges.' Ed. DD Briske) pp. 25-84. (Springer International Publishing: Cham)

Ash A, Hunt L, McDonald C, Scanlan J, Bell L, Cowley R, Watson I, McIvor J, MacLeod N (2015) Boosting the productivity and profitability of northern Australian beef enterprises: Exploring innovation options using simulation modelling and systems analysis. *Agricultural Systems* **139**, 50-65.

Barlow S, Grace P, Stone R, Gibbs M, Howden S, Howieson J, Ugalde D, Miller C, Eckard R, Rowland S (2010) National Climate Change Adaptation Research Plan: Primary Industries. *National Climate Change Adaptation Research Facility, Griffith University, Qld*.

Barnes ML, Wang P, Cinner JE, Graham NAJ, Guerrero AM, Jasny L, Lau J, Sutcliffe SR, Zamborain-Mason J (2020) Social determinants of adaptive and transformative responses to climate change. *Nature Climate Change* **10**(9), 823-828.

Bowen M, Chudleigh F, Perry L (2020) Northern Downs beef production systems - Preparing for, responding to, and recovering from drought. Department of Agriculture and Fisheries, Queensland Government.

Boyd EJ (2017) Climate adaptation: holistic thinking beyond technology. *Nature Climate Change* **7**(2), 97-98.

Bray SG, Allen DE, Harms BP, Reid DJ, Fraser GW, Dalal RC, Walsh D, Phelps DG, Gunther R (2016) Is land condition a useful indicator of soil organic carbon stock in Australia's northern grazing land? *The Rangeland Journal* **38**(3), 229-243.

Burns BM, Fordyce G, Holroyd RG (2010) A review of factors that impact on the capacity of beef cattle females to conceive, maintain a pregnancy and wean a calf - Implications for reproductive efficiency in northern Australia. *Animal Reproduction Science* **122**, 1-22.

Callaghan MJ, Tomkins NW, Hepworth G, Parker AJ (2020) The effect of molasses nitrate lick blocks on supplement intake, bodyweight, condition score, blood methaemoglobin concentration and herd scale methane emissions in *Bos indicus* cows grazing poor quality forage. *Animal Production Science* **61**(5), 445-458.

Charmley E, Williams SRO, Moate PJ, Hegarty RS, Herd RM, Oddy VH, Reyenga P, Staunton KM, Anderson A, Hannah MC (2016) A universal equation to predict methane production of forage-fed cattle in Australia. *Animal Production Science* **56**(3), 169-180.

CSIRO (2020) 'LOOC-C A landscape options and opportunities for carbon abatement calculator.' Available at https://looc-c.farm [accessed 2021]

CSIRO, Bureau of Meteorology (2015) Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report. CSIRO and Bureau of Meteorology, Australia.

Dass P, Houlton BZ, Wang Y, Warlind D (2018) Grasslands may be more reliable carbon sinks than forests in California. *Environmental Research Letters* **13**(7), 074027.

Davidson D (2016) Gaps in agricultural climate adaptation research. *Nature Climate Change* **6**(5), 433.

FarmBot (2021) Monitor your water remotely with FarmBot. Customer Product guide. In. ' Ed. FM Solutions). (FarmBot: farmbot.com.au)

Fensham RJ, Fairfax RJ (2005) Preliminary assessment of gidgee (*Acacia cambagei*) woodland thickening in the Longreach district, Queensland. *The Rangeland Journal* **27**(2), 159-168.

Fensham RJ, Fairfax RJ, Archer SR (2005) Rainfall, land use and woody vegetation cover change in semi-arid Australian savanna. *Journal of Ecology* **93**(3), 596-606.

Fordyce G, McCosker KD, Barnes TS, Perkins NR, O'Rourke PK, McGowan MR (2023) Reproductive performance of northern Australia beef herds. 6. Risk factors associated with reproductive losses between confirmed pregnancy and weaning. *Animal Production Science* **63**(4), 365-377.

Freer M, Dove H, Nolan JV (2007) 'Nutrient Requirements of Domesticated Ruminants.' (CSIRO Publishing: Collingwood)

FutureBeef (2022) 'Vaccinations for cattle.' Available at https://futurebeef.com.au/resources/vaccinations-beef-cattle/ [accessed September 2023]

Gardener CJ, McIvor JG, Jansen A (1993) Passage of Legume and Grass Seeds Through the Digestive Tract of Cattle and Their Survival in Faeces. *Journal of Applied Ecology* **30**(1), 63-74.

Gardiner C, Bielig L, Schlink A, Coventry R, Waycott M (2004) Desmanthus a new pasture legume for the dry tropics. In 'Proceedings of the 4th International Crop Science Congress. ' Brisbane, Australia)

Gaughan JB, Mader TL, Holt SM, Sullivan ML, Hahn GL (2010) Assessing the heat tolerance of 17 beef cattle genotypes. *International Journal of Biometeorology* **54**(6), 617-627.

Guarte JM, Barrios EB (2006) Estimation Under Purposive Sampling. *Communications in Statistics - Simulation and Computation* **35**(2), 277-284.

Holzworth D, Huth NI, Fainges J, Brown H, Zurcher E, Cichota R, Verrall S, Herrmann NI, Zheng B, Snow V (2018) APSIM Next Generation: Overcoming challenges in modernising a farming systems model. *Environmental Modelling & Software* **103**, 43-51.

Honda EA, Durigan G (2016) Woody encroachment and its consequences on hydrological processes in the savannah. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**(1703), 20150313.

Leith P, Haward M (2010) Climate Change Adaptation in the Australian Edible Oyster Industry: an analysis of policy and practice. University of Tasmania, Hobart.

MacLeod N, Mayberry D, Revell C, Bell L, Prestwidge D (2018) An exploratory analysis of the scope for dispersed small scale irrigation developments to enhance the productivity of northern beef cattle enterprises. *The Rangeland Journal* **40**, 381-399.

McCosker K (2023) Providing artificial shade in relatively treeless rangelands to increase calf survival. In 'QAAFI Science Seminars. ' (QAAFI: online recording)

McGowan M, McCosker K, Fordyce G, Smith D, O'Rourke P, Perkins N, Barnes T, Marquart L, Morton J, Newsome T, Menzies D, Burns B, Jephcott S (2014) Northern Australian beef fertility project: CashCow. Sydney.

McLean I, Holmes P (2015) Improving the performance of northern beef enterprises, 2nd edition. Meat & Livestock Australia.

McLennan S, McLean I, Paton C (2020) Re-defining the animal unit equivalence (AE) for grazing ruminants and its application for determining forage intake, with particular relevance to the northern Australian grazing industries. Meat and Livestock Australia, North Sydney.

Mortreux C, Barnett J (2017) Adaptive capacity: exploring the research frontier. *WIREs Climate Change* **8**(4), e467.

Nelson D, Adger W, Brown K (2007) Adaptation to Environmental Change: Contributions of a Resilience Framework. *Annual Review of Environment and Resources* **32**(1), 395-419.

Nettle R, Kuehne G, Lee K, Armstrong D (2018) A new framework to analyse workforce contribution to Australian cotton farm adaptability. *Agronomy for Sustainable Development* **38**, 38.

O'Brien K, Hochachka G (2010) Integral adaptation to climate change. *Journal of Integral Theory and Practice* **5**(1), 89-102.

Orr DM, Phelps DG (2013) Impacts of level of utilisation by grazing on an *Astrebla* (Mitchell grass) grassland in north-western Queensland between 1984 and 2010. 1. Herbage mass and population dynamics of *Astrebla* spp. *The Rangeland Journal* **35**(1), 1-15.

Patton MQ (2015) 'Qualitative research & evaluation methods: Integrating theory and practice.' (SAGE Publishing)

Petheram C, Watson I, Stone P (2013) Agricultural resource assessment for the Flinders catchment. A report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy. . CSIRO, Canberra.

Phelps D (2012) Best-bet practices for managing the Mitchell grasslands of Queensland. A technical guide of options for optimising animal production, profitability and land condition. Department of Employment, Economic Development and Innovation, Longreach.

Phelps D (2019) The north-west Queensland Monsoon event of 26 January – 9 February 2019 : report of a landholder survey into impact and recovery. Queensland Government.

Preston B, Stafford-Smith M (2009) Framing vulnerability and adaptive capacity assessment: discussion paper. *CSIRO Climate Adaptation Flagship Working paper No. 2.*

Pringle MJ, Allen DE, Dalal RC, Payne JE, Mayer DG, O'Reagain P, Marchant BP (2011) Soil carbon stock in the tropical rangelands of Australia: Effects of soil type and grazing pressure, and determination of sampling requirement. *Geoderma* **167-168**, 261-273.

Pringle MJ, Allen DE, Phelps DG, Bray SG, Orton TG, Dalal RC (2014) The effect of pasture utilization rate on stocks of soil organic carbon and total nitrogen in a semi-arid tropical grassland. *Agriculture, Ecosystems & Environment* **195**, 83-90.

Queensland Government (2011) Mitchell Grass Downs region Grazing Land Management land type information version 3.1. Future Beef.

Queensland Government (2023a) 'Drought Declarations Archive.' Available at https://www.longpaddock.qld.gov.au/drought/archive/ [accessed 2023]

Queensland Government (2023b) SILO - Australian climate data from 1889 to yesterday Q Government

Rickards L (2014) Climate Change Adaptation in the Australian Primary Industries: An Interpretive Review of Recent Literature. Primary Industries Adaptation Research Network.

Rickert KG, Stuth JW, McKeon GM (2000) Modelling pasture and animal production. In 'Field and Laboratory Methods for Grassland and animal Production Research.' (Eds L 't Mannetje and RM Jones). (CABI publishing: New York)

Sietsma AJ, Ford JD, Callahan MW, Minx JC (2021) Progress in climate change adaptation research. *Environmental Research Letters* **16**(5), 084038.

Smit B, Wandel J (2006) Adaptation, adaptive capacity and vulnerability. *Global Environmental Change* **16**(3), 282-292.

Stevens N, Lehmann CER, Murphy BP, Durigan G (2017) Savanna woody encroachment is widespread across three continents. *Global Change Biology* **23**(1), 235-244.

Stokes C, Jarvis D, Webster A, Watson I, Jalilov S, Oliver Y, Peake A, Peachey A, Yeates S, Bruce C, Philip S, Prestwidge D, Liedloff A, Poulton P (in press) Financial and socio-economic viability of irrigated agricultural development in the Roper catchment. A technical report from the CSIRO Roper River Water Resource Assessment for the National Water Grid Authority. CSIRO.

Suybeng B, Charmley E, Gardiner CP, Malau-Aduli BS, Malau-Aduli AEO (2020) Supplementing Northern Australian Beef Cattle with Desmanthus Tropical Legume Reduces In-Vivo Methane Emissions. *Animals* **10**(11).

Syktus J, Trancoso R, Ahrens D, Toombs N, Wong K (2020) 'Queensland Future Climate Dashboard: Downscaled CMIP5 climate projections for Queensland.' Available at https://www.longpaddock.qld.gov.au/qld-future-climate/ [accessed 1 June 2021]

Tedeschi LO, Fox DG (2020) 'The Ruminant Nutrition System Volume 1 - An Applied Model for Predicting Nutrient Requirements and Feed Utilization in Ruminants.' Third Edition edn. (XanEdu: Ann Arbor, USA)

Thornton P, Nelson G, Mayberry D, Herrero M (2022) Impacts of heat stress on global cattle production during the 21st century: a modelling study. *The Lancet Planetary Health* **6**(3), e192-e201.

Tyler R, English B, Sullivan M, Jackson D, Matthews R, Holmes B, MacDonald N, Oxley T, Leigo S, Smith P (2012) Weaner management in northern beef herds. Meat and Livestock Australia, North Sydney.