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Impacts of environmental feedbacks on the production of a Central Queensland beef enterprise in a future climate

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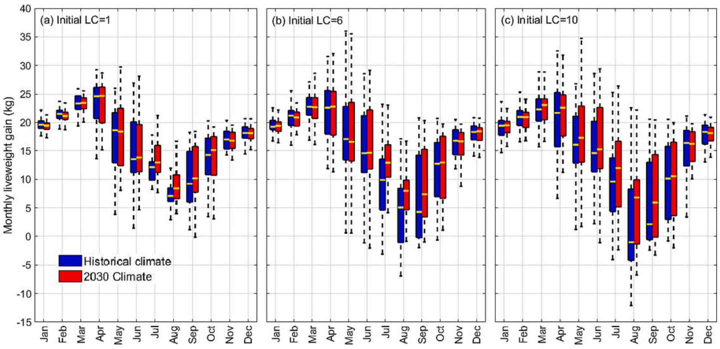
HIGHLIGHTS

- Climate change impacts on beef production enterprise.
- A holistic impact assessment distilled from individual ruminants.
- A warmer future will increase pasture growth in winter, being important for animal liveweight gain.
- A drier future will reduce the sustainable herd size, beef production and thus profitability.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Understanding climate change impacts on beef production enterprises in northern Australia is challenging due to the complexity of the system, which involves biophysical processes such as pasture and animal production, herd management, economics, emissions, and the interaction among these things. Modelling is a powerful tool to help the beef industry understand the impacts of climate change and to develop adaptation plans to help ensure enterprises remain economically viable over the long term.

OBJECTIVE: We assess climate change impacts on a single specialised beef enterprise south-east of Moura (24.59°S, 150.09°E) in northern Australia's Central Queensland region. This is achieved by comparing enterprise performances during a 2030s climate and a 1975–2013 baseline period.

METHODS: We used a calibrated pasture model called GRASP to simulate the farm's pasture growth under multiple scenarios for land conditions, grass basal areas and stocking rates for the baseline and 2030s climates and to construct pasture growth databases – known as datacubes. The datacubes provide a simplified representation of mean coupling between the herd dynamics and livestock production model (Crop Livestock Enterprise Model). The coupled whole-of-farm model was parameterised using enterprise data collected through

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interviews with the property owner and allowed for feedback between the pasture and livestock systems. The feedback capability allowed us to consider changes in land condition through stocking rates and their effect on pasture growth, animal weight gain, profit and CO_2 emissions.

RESULTS AND CONCLUSIONS: We found that warmer and drier climatic conditions during 2030s will reduce pasture growth in austral spring and summer but increase pasture growth in winter and autumn. Increased pasture growth in winter and autumn cannot compensate for the reduction in pasture growth in the warm seasons but can improve animal liveweight gain in winter and early spring. This leads to an overall increase in annual weight gain of steers (the cattle class that provides the main income source for this farm) while the CO_2 emission intensity remains similar to the baseline period. Maintaining land condition under the 2030s climatic conditions considered will require a reduction in sustainable herd size, leading to lower beef production and lower profit under current pasture and herd management strategies. Impacts will likely differ from those described if a drier future is not realised.

SIGNIFICANCE: This study provides a climate change impact assessment on a specialised beef enterprise (i) being distilled from individual ruminants, and (ii) considering environmental feedbacks in the interaction between pasture and livestock systems.

1. Introduction

Australia is a major beef producer contributing substantially to global beef trade and food security (MLA, 2022). Pasture-based livestock production systems around the world are facing the challenges of a changing climate with more frequent and impactful weather extremes (Brás et al., 2021). Climate change, together with other pressures such as an increasing percentage of farm cash receipts required to service rising debt (Thompson and Martin, 2014), rising production and marketing costs (Fariña et al., 2013), and a stabilising trend of long-term beef price (MLA, 2022), threatens the economic viability of some of these specialised beef production systems.

The future climate is projected to be warmer with increased frequency and intensity of heatwaves and extreme daily rainfall (IPCC, 2021). In north-eastern Australia, rainfall has increased over the past century (CSIRO and Bureau of Meteorology, 2015; Heidemann et al., 2023). However, rainfall projections for the coming decades are uncertain (Grose et al., 2020; Heidemann et al., 2023), and natural climate variability is projected to remain a major driver of rainfall changes in the next few decades (Kirtman et al., 2013; Lee et al., 2021). Coupled climate models show a range of projections, with the consensus indicating little change or decrease in rainfall (Grose et al., 2020, Heidemann et al., 2023). In terms of recent observed trends since 1950, most of Queensland has experienced a drier climate, while the Northern Territory and northern Western Australia have experienced wetter conditions (Fig. 1).

Based on the Australian Climate Observations Reference Network - Surface Air Temperature (ACORN-SAT v2.4) dataset, over the 1950–2015 period it has significantly warmed across most of the country, except for northwest Western Australia (see supplementary Fig. S1). Queensland, NSW and South Australia have warmed by between 0.2 and 0.3 °C/decade. As a result of wetter conditions across the northwest of Australia, it is the one region that has seen the least amount of warming, between 0 and 0.05 °C/decade. Since records began in 1910, Australia, as a whole, has warmed by 1.47 ± 0.24 °C. According to the 2022 State of the Climate Report, published by the Bureau of Meteorology and CSIRO, Australia will continue to warm into the near and long-term future. Australia's average annual surface temperature range for 2021–2040, relative to 1850–1900, will be about 1.7–2.4 °C (one standard deviation). By the mid-century (2040–2059, surface temperatures across the north and east coast are expected to be 1–2 °C warmer than the 1986–2005 average, depending on whether the world follows a low, medium or high emission scenario. These projections come from downscaled and bias corrected climate models from CMIP5 (CSIRO, 2022).

Unfortunately, there is limited information on how climate change will impact the grazing feed base which mostly includes natural C_4 tropical and subtropical grasses (Ash et al., 2015; Cobon et al., 2020) in our region of interest in central Queensland. More specifically, there has not been a holistic enterprise-level study analysing how climatic events impact the whole farm system, from pasture biomass production to herd dynamics and live weight gain, through to selling and destocking requirements and profit. Such a study needs to also consider the feedbacks of herd dynamics via the impacts of stocking rates on the pasture system through driving changes in land condition, grass basal area, and ultimately pasture growth rates.

Here we conduct such a holistic study and examine the potential impacts of climate change on a pasture-based specialised beef enterprise[1] with respect to seasonality of pasture production, herd dynamics, live weight gain, profitability, and CO_2 emission. This will lead to a better understanding of both the challenges and the possible opportunities that climate change presents.

We will use process-based models which provide us with a cost-effective opportunity to explore the response of specialised beef enterprises to projected future climate change. These enterprises consist of complex herd structures and dynamics that are subject to interactions between climate variability and pasture resources, which drives considerable production risk (Cacho et al., 1999). Further to this, complex herd dynamics can affect the pasture system through a feedback mechanism, driving significant environmental risk (Scanlan et al., 2014). For example, it is possible that a potential reduction in pasture growth while maintaining the current herd size (animal number) can run the risk of unintended deterioration in the health of the land and ecosystem.

Beef cattle simulation models have been developed for different production systems around the world (e.g., Foran et al., 1990; Tess and Kolstad, 2000; Teague and Foy, 2002). However, the available models are not particularly suited for simulating extensive production systems in sub-tropical and tropical regions (Ash et al., 2015). Other simulation models that have been specifically developed for northern Australia beef systems do capture the highly variable climate-pasture dynamics (McKeon et al., 2000) but rely on simple empirical relationships established between pasture growth and liveweight gain (McCown, 1981) to drive animal production and enterprise economics.

The Crop and Livestock Enterprise Model (CLEM) (Laing and Liedloff, 2023) was developed to enable simulation of whole-of-farm enterprises, including both crop and livestock production and enterprise economics. CLEM was designed to be flexible by adopting a modular approach and can be scaled to simulate extensive beef systems on northern Australian pastures. CLEM models the energy and protein consumed by animals and its conversion into animal growth, body condition and reproductive capability. CLEM is the first enterprise model in Australia with the capability to simulate and trace individual ruminants and is far more customisable for the northern Australia herds than any other available model. CLEM, however, currently cannot assess

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[1] In Australia, a specialised beef enterprise indicates a livestock farm of solely beef cattle.

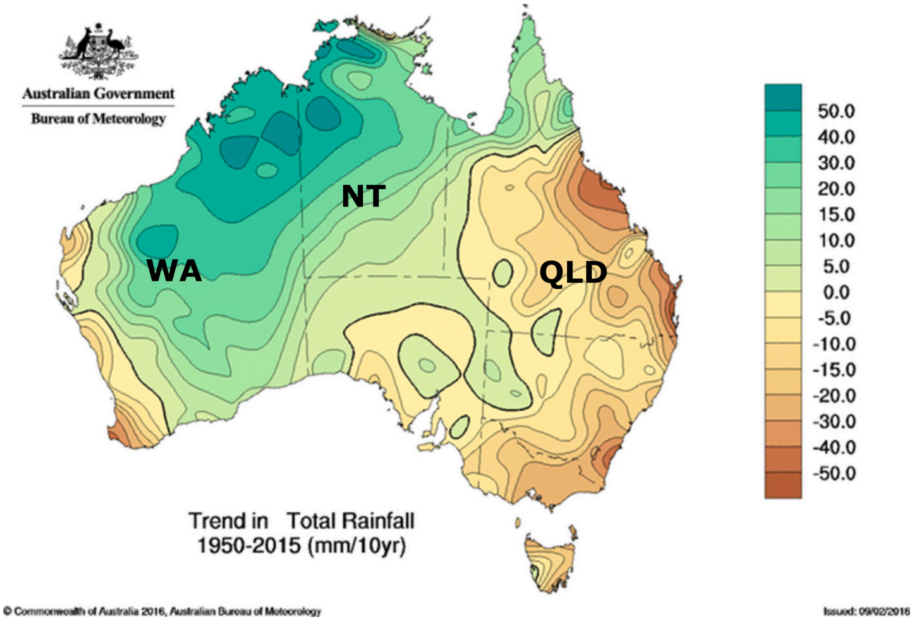

Fig. 1. Spatial map of trend of total annual rainfall for Australia, from 1950 to 2015. QLD is Queensland, NT is Northern Territory, and WA is Western Australia (WA).

the direct impacts of climate change on animal such as the heat stress on cattle or on reproductive performance of the cows, which are areas of ongoing research and development.

The flexibility of CLEM allows integration with GRASP (Rickert et al., 2000), a model widely used for simulating pasture production in tropical and subtropical regions (McKeon et al., 2009; Scanlan et al., 2013). The development of GRASP over >30 years has concentrated on drought effects on pastures in northern Australia and how to adequately simulate the effects. We developed an integrated simulation model, by coupling pasture simulation using GRASP with herd dynamic simulation using CLEM, to achieve the first-ever holistic climate change impact assessment model for a specialised beef enterprise in central Queensland. We should note that it is beyond the scope of this work as a user application of GRASP and CLEM to provide full model descriptions. Some papers solely describing the modelling approaches and details of CLEM are currently being submitted by the developers.

2. Materials and methods

Australian beef farming occurs in diverse climatic zones, but the dominant extensive specialised beef operations occur in northern tropical and subtropical regions that experience cold dry winters and hot wet summers. The state of Queensland has Australia's largest beef cattle herd (10.7 million head) and is the nation's largest producer and exporter of beef. We undertook a case study of a typical beef enterprise near Moura in Central Queensland (largest herd size in Australia) and is representative of breeder enterprise with a defined breeding period in summer, variable but relatively fertile soils, summer dominant rainfall and moderate to high interannual rainfall variability – characteristics of many beef enterprises in tropical and sub-tropical northern Australia (Bowen and Chudleigh, 2018).

2.1. The case study enterprise

The property is located south-east of Moura in the Banana shire (24.59°S, 150.09°E; Fig. 2(a) and (b)) and has a total area of 8800 ha, average annual precipitation of 630 mm, long-term annual mean temperature of 21.4 °C (1975–2013) and woody vegetation covers approximately 1.3% of the property. The warmer months of November to February also experience the highest average rainfalls (Fig. 2(c)), and summer is the growing season while winter is dry with very limited pasture growth. Land types include Brigalow with blackbutt (Dawson gum) (65% of the area of the property), Poplar box with shrubby understorey (27%), Blue gum/river red gum flats (3%), Brigalow softwood scrub (3%), Mountain coolibah woodlands (2%), and Softwood scrub (<1%). Soil types include Brigalow belah, red loams, and black clay. Water use is currently all surface water from dams.

For a location like Moura, coupled climate models show a range of rainfall projections, with the consensus indicating little change or decrease in rainfall (Grose et al., 2020; Heidemann et al., 2023). The frequency of heatwaves will likely increase. This is based on downscaled (and bias corrected) CMIP5 projections. Here, a heatwave is defined as 3 consecutive days of maximum temperatures above 34 °C and minimum temperatures above 22 °C. Similar increases in heatwave frequency are projected across central QLD. As shown in supplementary Fig. S2, under a high emission scenario (i.e., RCP8.5), the number of events could increase from 3 events per year (1993–2022) to 7 events per year (2036–2065).[2] Even in a medium emissions scenario, the frequency of heatwaves will likely increase to 6 events per years (2036–2065).

The beef herd at the enterprise is a self-replacement breeding herd with *Bos indicus* breed on improved pasture, mainly selling steers. The manager does not buy female breeders and the heifers replace old female breeders at 24 months for first mating. The size of this breeding herd is thus governed by the number of female breeders. As of June 2019, the herd size is 3300 heads (close to 3500 adult equivalents (AE)) consisting of cows, calves, steers, bullocks and bulls. More details of the herd structure including age, average weight, and number of each cattle class can be found in Table S1. The controlled mating program joins females from December to February with calving in late spring/early summer the year after. Weaning operation is conducted in April by age and weight. Animal numbers are adjusted by the enterprise manager in

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[2] These are based on downscaled climate model information from CMIP5 and Bureau of Meteorology AGCD observations. Information taken from https://myclimateview.com.au/.

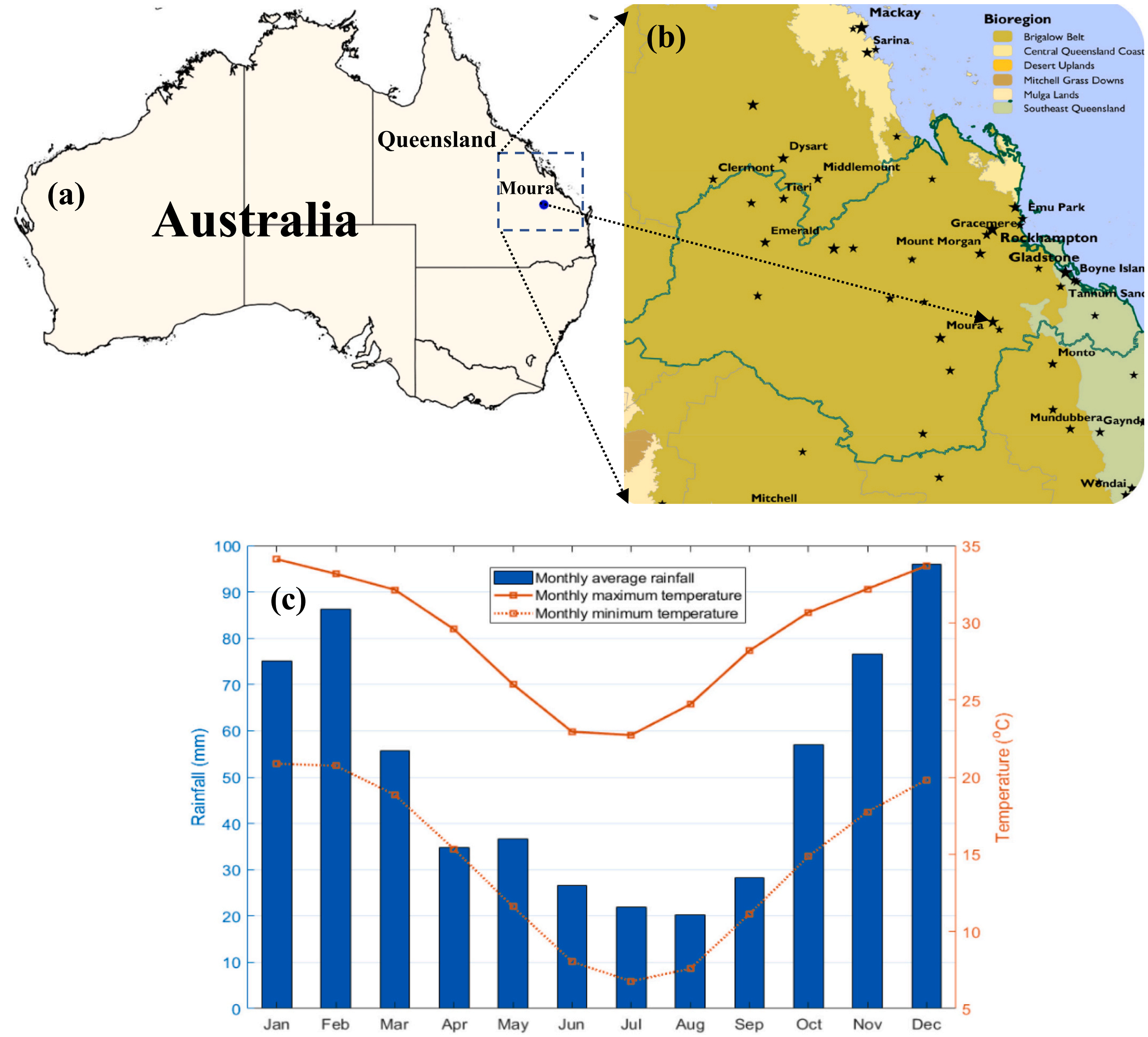

Fig. 2. (a) and (b) location of the specialised beef enterprise in south-east of Moura; (c) climatic conditions recorded at the Moura station (https://www.longpaddock.qld.gov.au/silo/) averaged over the baseline period (1975–2013).

response to seasonal conditions in May[3] and mustering in August, with cows retained up to the age of 18 years and steers until they reach 600 kg (which is usually 3.5 years). The average birthweight is 38 kg with an average growth rate of 0.5 kg/day.

For this study, the property represented in the models (outlined in Section 2.4) is also representative of other enterprises in the region (regional advisory committee – pers. com). We conducted interviews with the enterprise manager to collect detailed husbandry and production costs for an economic analysis (see the cost of production in the supplementary Table S2). The regional advisory committee was established with four members, comprised of farmers and local service providers. This committee provided input into the assumptions used when analysing the farming system. The committee members also contributed to the interpretation of the results to ensure that the assessment conducted was subjected to informed feedback and that a range of perspectives were considered.

2.2. Climate change scenarios

The regional climate change projections for 2030 were obtained from the Climate Change in Australia Futures Tool[4] (CSIRO and Bureau of Meteorology, 2015). This provides monthly projected changes in temperature and rainfall in the Australian East Coast Cluster based on a high emissions scenario (Representative Concentration Pathway 8.5). To account for the variation in climate projections among ensembles generated by General Circulation Models (also known as climate

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[3] When the herd is destocked to ensure a minimum pasture biomass of 500 kg per ha is retained in November to avoid overgrazing. It is assumed that there are no further pasture inputs through pasture growth during every dry winter. Old sires, old female breeders, and castrated males were selected for destocking.

[4] https://www.climatechangeinaustralia.gov.au/en/projections-tools/climate-futures-tool/projections/

models), Low (low impact), Maximum Consensus (average impact) and High (high impact) change scenarios were developed. As can be seen in Table 1, there is a high agreement among climate models that Australia's east coast will be 1 °C warmer by 2030s compared to a 1975–2013 base period. However, there is a wide range in rainfall projections for all the months, and it is unclear if the eastern Australia will be drier (high impact) or wetter (low impact) in the region of interest (Fig. 3). For this case study, we will focus on the projections for which the largest number of models agree which we refer to as the Maximum Consensus "Storyline". The results of Low and High-impact scenarios will be reported in a future study.

The monthly projected changes were used in the change calculator prepared and described by Harrison et al. (2016) to perturb the historical daily climate data (1975–2013) and generate a climate file for 2030s – future daily climate data at the studied enterprise, including the projected changes in extreme events. The 2030s climate in this study was thus generated and defined by the employed downscaling approach (Harrison et al., 2016) for the case study site where the projected monthly changing factors of the target time horizon – 2030s – are used to modified daily climate data of the baseline period, 1975–2013 (39 years period). Hence, the 2030s climate here indicates the climate of the 39 years realization inherited the order of the baseline years 1975–2013 with the included climate change projection for 2030s. We sourced historical weather data for the case study site from meteorological archives (http://www.longpaddock.qld.gov.au/silo). These historical and 2030s climate files were then used in GRASP for the simulation of pasture growth.

2.3. Pasture growth simulation and pasture datacubes

Pasture growth was simulated with the Cedar version of GRASP (Windows). All simulations were run at a daily time step employing historical (1975–2013) and 2030s climate data as described above. Soil attributes, land and pasture (supplementary Table S4) were parameterised from similar soils and improved pastures (Buffel grass) from long-term grazing trial data at Brigalow Research Station (Dalal et al., 2021). Buffel is an introduced/naturalised species which is drought tolerant within the range of native species in the region. No parameterisation for climate change was completed within GRASP (only the climate files were different).

The GRASP pasture growth model also calculated evapotranspiration (ET) at a daily time step, using the climate data inputs of temperature, rainfall, radiation and vapour pressure to simulate model processes (both current climate and 2030s climate). The daily soil water balance was calculated as the difference between inputs (rainfall) and outputs (runoff, drainage, canopy evaporation, soil evaporation and transpiration by grass and trees) in four soil layers of variable thickness and water holding characteristics. The components of ET including pasture and tree transpiration and soil evaporation are calculated separately from potential rates that are adjusted based on soil water availability. Any change in the climate (rainfall, temperature, radiation, vapour pressure) will impact upon the simulated water balance processes, ET, soil water and pasture growth. Detailed descriptions of the GRASP model and equations are presented in (Day et al., 1997).

Table 1
Projected monthly changes in average temperature by 2030s compared to the base period (1975–2013) for the Australian East Coast Cluster, and the degree of consensus among climate models on the change.

Month	Mean temperature change (°C)	Consensus (%)
January	0.5 to 1.5	90
February	0.5 to 1.5	85
March	0.5 to 1.5	78
April	0.5 to 1.5	84
May	0.5 to 1.5	79
June	0.5 to 1.5	75
July	0.5 to 1.5	79
August	0.5 to 1.5	82
September	0.5 to 1.5	87
October	0.5 to 1.5	88
November	0.5 to 1.5	85
December	0.5 to 1.5	95

The GRASP model was run for both the historical and 2030s climate to generate monthly pasture growth for each combination of the following factors:

- Grass basal area (%) ranging from 1 to 6 (8 values: 1, 1.5, 2, 2.5, 3, 4, 5, 6). This range represents the possible variability in grass basal area in our simulated case study.
- Land condition ranging from 0 to 11 (12 values) – 0 indicates the best land condition while 11 is the worst (supplementary Table S5). This range allows us to study climate change impacts on the studied enterprise at varied initial land conditions from very good to very poor.
- Stocking rate (AEs per 100 ha) ranging from 1 to 70 (23 values: 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70). This range represents the possible variability in stocking rate in our simulated case study.

The total number of GRASP simulations for the historical climate was 2208, being equivalent to 8 × 12 × 23 combinations of grass basal area × land condition × stocking rate. The same number of GRASP simulations for the same combinations were conducted using the modified 2030s climate. These simulations show the effect of combined grass basal areas, land conditions and stocking rates on pasture growth. Grass basal area is important in the GRASP pasture model as it drives initial regrowth at the start of the growing season. It is also an important indicator of resource condition (both pasture and land condition). Land condition determines the productivity of the land resource from the viewpoint of pasture and animal production as well as land management, with grazing management having a major impact on pasture condition.

Note that a stack input file for the GRASP model was generated including all the model parameters for the case study together with the combinations. These 2208 combinations were automatically constructed using a Python script created by Chris Stokes (pers com.). The simulated monthly pasture growths were used to construct two datacubes for the historical and 2030s climates. To do this, a Matlab code was developed to read and process the factorial GRASP simulation outputs, connect to a database tool (DB Browser), and put the processed factorial outputs into a database file (see Table S6 for the format of this database). These datacubes (database files) were then read by a CLEM component – FileSQLitePasture, for feedback simulation explained in Section 2.5.

2.4. Livestock beef enterprise model

We used CLEM – a first livestock enterprise model in Australia with the simulation capability of individual ruminants – to build a whole-of-farm model for our case study beef enterprise which is a production system solely consuming improved pasture – Buffel grass (*Cenchrus ciliaris*) pastures are the dominant pastures at the study site. Simulated monthly pasture growth at the beef enterprise were stored in the developed datacubes, and then coupled with CLEM to represent pasture productivity. More details on management of pasture (including datacube coupling mechanism) and the herd in CLEM can be found in the supplementary sections 2, 3 and 4. CLEM can test a range of management strategies in livestock systems by assessing impacts on finances, natural resources, and constraints such as labour at monthly time step. The modular approach in CLEM provides a fully customisable and flexible set-up for complex whole-of-farm simulations to be performed. The CLEM model also allows users to study climate change impacts on herd dynamics, especially the differences in enterprise performance, including environmental consequences through a coupling mechanism

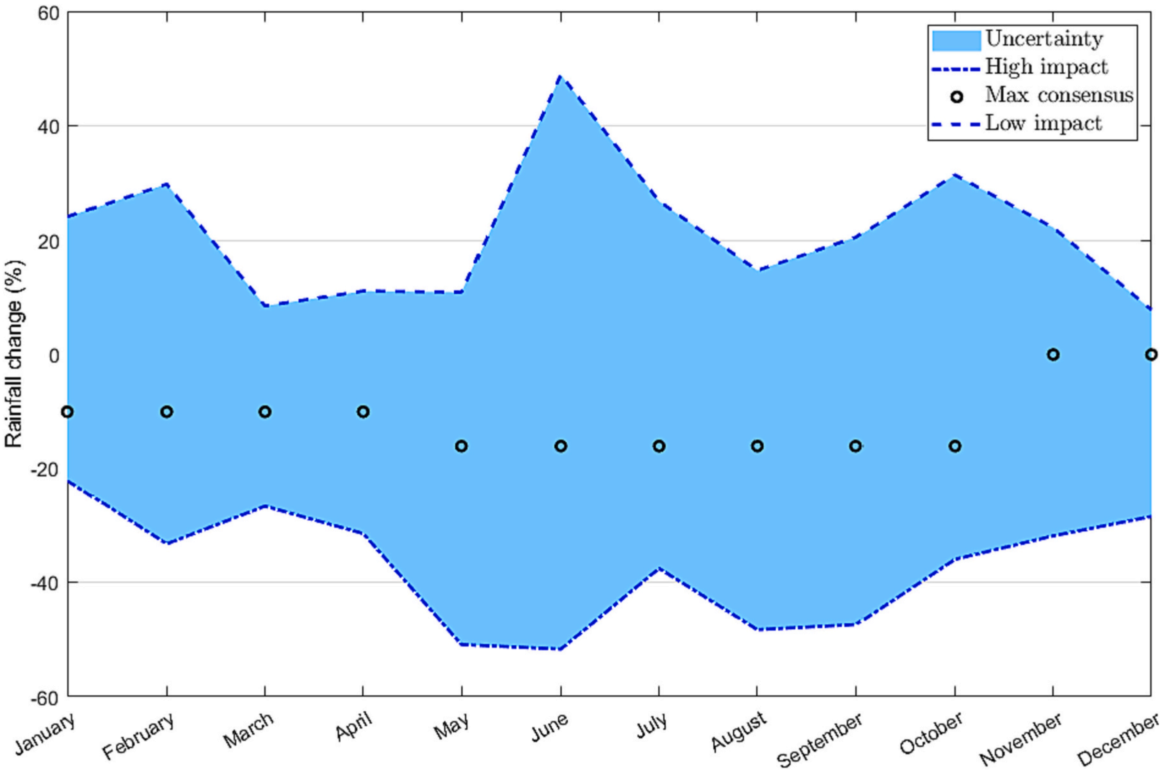

Fig. 3. Projected monthly rainfall changes by 2030s compared to the base period (1975–2013) averaged over the Australian East Coast Cluster.

between GRASP and CLEM, allowing the simulation of feedbacks of the herd dynamics on pasture growth, as described in the next subsection.

2.5. *Feedback simulation*

We coupled CLEM with the developed pasture datacubes, allowing a two-directional interaction (i.e., feedback) between the pasture system and the livestock system for the case study beef enterprise. Such advanced CLEM feedback simulations provide the opportunity to study the climate change impacts on the beef enterprise in a meaningful way through the tracing performances of individual ruminants including weight, growth, and activities. Individual animal data were modelled and where stochastic events (conception, pregnancy success, suckling survival) in the model allow the weight of individuals in the same cohort to deviate. The feedback simulations also allow us to explore the dynamics of land conditions, grass basal areas (GBA), stocking rates and their effects on pasture growth.

It is possible that climate change impacts might differ depending on the initial condition of the studied land resource. We analysed the performances of the beef enterprise in the historical climate and the 2030s climate with a scenario of initial land conditions, using the CLEM feedback simulations. While the current land condition at the beef enterprise is close to moderate – land condition index of 6 – we also simulated the climate change impacts at good initial land condition (land condition index of 1) and poor initial land condition (land condition index of 10). The developed CLEM feedback model tracks land condition and grass basal area as a function of monthly pasture utilisation rates based on reported relationships (Figs. S4 and S5) and safe utilisation rates. When model runs the initial land condition changes between 0 (very good) to 11 (very poor, Table S5) reflecting the transient utilisation percentage and stocking rate at the studied beef enterprise. When the utilisation percentage is higher than 30% or 20%, the land condition or grass basal area is degraded, respectively (Figs. S4 and S5), and vice versa.

To avoid overgrazing and long-term land degradation in the feedback simulation runs, we firstly conducted a number of trial runs at each initial land condition in both the historical and 2030s climates by varying the parameter named "*maximum number of female breeders to be retained*" in CLEM from 900 to 1500 in steps of 50. At each run, the time series of land condition and accumulated income of the beef enterprise were recorded. The optimal parameter was determined for each initial land condition which maximises the total accumulated income of the beef enterprise while maintaining or improving the long-term land condition which was monitored by plotting the recorded land condition time series. Herd simulation data using this optimal parameter at each initial land condition were used to estimate the optimal sustainable herd size (OSHS) which is the average herd size over the financial years in terms of adult equivalents (AEs). The OSHS at each initial land condition represents the maximum long-term average herd size at the studied beef enterprise that does not degrade the initial land condition. Economic analysis was conducted for each simulation scenario to estimate the enterprise gross margin (supplementary section 1) as an indicator of the enterprise profitability.

3. Results

3.1. *Projected 2030s climate*

The projected 2030s climate exhibits a reduction in the average and standard deviation of total annual rainfall relative to the reference period, contributed to by a slight reduction in the magnitude and number of wet-day[5] events (Table 2). There was a small increase in the number and duration of dry spells which indicates added pressure on soil water levels. Average maximum and minimum temperatures increased by 1 °C and 0.5 °C, respectively, leading to an increased daily temperature range (Table 3). The largest increase was marked by the number of hot days (max $T >$ 90histmax) per year increasing from 35

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[5] A wet day is a day having >1 mm rainfall.

Table 2
Historical and 2030s rainfall (R) indices. Statistics are expressed from computations using 39 years of climate data (avg. = average, st. dev. = standard deviation).

Variable	Unit	Historical	2030s climate
Avg. total annual rain	mm/yr	616	569
St. dev. Total annual rain	mm/yr	164	151
Avg. no. dry days	d/yr	312	314
Avg. no. wet days	d/yr	53	51
Avg. max contiguous duration of dry days	d/yr	55	57
Avg. max contiguous duration of wet days	d/yr	5	5
Avg. max wet day event	mm/d	71	68
Avg. wet day rain (R_d)	mm/d	11.5	11.2
St. dev. of R_d	mm/d	2.2	2.3
10th percentile of R_d	mm/d	1.5	1.5
50th percentile of R_d	mm/d	6.3	5.6
90th percentile of R_d	mm/d	28.2	27.4
95th percentile of R_d	mm/d	38.5	37.4
99th percentile of R_d	mm/d	68.4	68.4

days in the historical climate to >66 days by 2030 (85% increase). The hot consecutive days were also longer at an average of >5 days (25% increase) as well as the longest hot period in a year at an average of >14 days (72% increase). While the average temperature increased by about 1 °C, the temperature of extreme hot days increased by 1.5 °C (90th and 95th percentile of max daily T), and 1.7 °C (99th percentile of max daily T). Relatively larger changes in the magnitude and frequency of extreme events could arise with smaller shifts in the mean or variance of a long-term distributions (Smith et al., 2001) which can be observed in the 2030s climate change scenario.

3.2. *Warmer 2030 climate increases pasture productivity in the cold half of a year*

Summer and spring pasture growth were simulated to be lower in the 2030s climate due to a reduction in seasonal rainfall, while winter pasture growth is projected to increase, owing to higher temperatures not limiting growth, causing a longer growing season (Fig. 4). The timing of improved growth in the colder months of the year varied according to initial land conditions. With good initial land condition (LC = 1), the starting month for improved growth was June while it occurred earlier in May and April, respectively, with moderate (LC = 6) and poor (LC = 10) initial land conditions. The 2030s climate indicated similar or reduced variability in pasture growth throughout the year compared to the historical climate. The relative variability in pasture growth and the 2030s climate impacts on reducing the variability increased if the initial land condition deteriorates. The higher growth in the colder months in the 2030s climate was not sufficient to outweigh the lower growth in summer and spring – shown by lower overall annual pasture productivity in the 2030s climate compared to those in historical climate in all land conditions (Table 4). Reductions in pasture biomass productivity in the 2030s climate were − 19, −9, and − 7%, respectively, for good, moderate, and poor land conditions. The pasture productivity gap between good and poor initial land conditions was thus reduced in the 2030s climate (33%) compared to that in the historical climate (52%). The good land condition has a high percentage of perennial grasses (Table S5). While established perennial grasses are more resilient to drought owing to better root systems, they are also quicker to respond to reduced rainfall than annual grasses that must establish from seed.

Table 3
Historical and 2030s temperature (T) indices. Statistics are expressed from computations using 39 years of climate data (avg. = average, st. dev. = standard deviation).

Variable	Unit	Historical	2030s climate
Avg. max daily T	°C	29.2	30.2
Avg. min daily T	°C	14.4	14.9
Avg. daily T range	°C	14.7	15.3
Avg. no. days max T > 90histmax	d/yr	35.8	66.3
Avg. no. consecutive days max $T >$ 90histmax	d/yr	4	5.1
Avg. max no. consecutive days max T > 90histmax	d/yr	8.2	14.1
Avg. no. days min T < 10histmin	d/yr	36.1	34.2
Avg. no. consecutive days min T < 10histmin	d/yr	4.1	4.0
Avg. max no. consecutive days min $T <$ 10histmin	d/yr	9.3	9.2
St. dev. of max daily T	°C	4.93	5.11
St. dev. Min daily T	°C	5.97	6.12
10th percentile of max daily T	°C	22.5	23.1
50th percentile of max daily T	°C	29.6	30.5
90th percentile of max daily T	°C	35.2	36.7
95th percentile of max daily T	°C	36.4	37.9
99th percentile of max daily T	°C	38.7	40.4
10th percentile of min daily T	°C	5.6	5.8
50th percentile of min daily T	°C	15.3	15.9
90th percentile of min daily T	°C	21.6	22.2
95th percentile of min daily T	°C	22.5	23.3
99th percentile of min daily T	°C	24.0	24.7

3.3. *Small improvement in pasture productivity can have significant effects on animal liveweight gain*

3.3.1. *Herd dynamics*

In the historical climate, the beef property could carry greater animal numbers than those in the 2030s climate in all initial land conditions, indicating a reduction in the optimal sustainable herd size[6] (OSHS) of 11–15% in the 2030s climate (Table 5). While the 2030s climate exhibits a slight increase in the variability in herd size, better initial land conditions allowed greater and more stable animal numbers (in both the historical and 2030s climates). Even with good initial land condition, the herd size was more vulnerable to drought in the 2030s climate, as represented in the number of months the herd size fell below 2000. This occurred only once (the blue dot in August fell below 2000) but 9 times (the red dots fell below 2000 not only in August but also in May, June, July, and September), respectively, in the historical and 2030s climates (Fig. 5; left panel). Note that the animal number largely decreased in August in all initial land conditions due to the selling of animals.

3.3.2. *Animal liveweight gain*

In the 2030s climate, there was an increase in monthly liveweight gain of steers (the cattle class for main income of the beef enterprise) in winter months in all land conditions (Fig. 6). Notably, owing to a warmer climate, small improvements in pasture growth rates in the colder months could increase liveweight gain which was carried over to September and October. The increased monthly liveweight gains and their variabilities were smaller with good land condition compared to those with moderate or poor land conditions.

Annually, despite the reduction in annual pasture production, a higher overall annual liveweight gain in all land conditions (Table 6) is projected. This highlights the important contribution of better winter growth due to a warmer climate in central Queensland. It should be noted that Fig. 6 showed increased liveweight gain per head, but the sustainable herd sizes needed to be reduced by 15%, 12% and 11% in the 2030s climate, respectively, for good, moderate, and poor initial land conditions (Table 5). The overall beef production per financial year

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[6] The optimal sustainable herd size is the herd size that does not deteriorate land condition in the long-term while maximises the enterprise income.

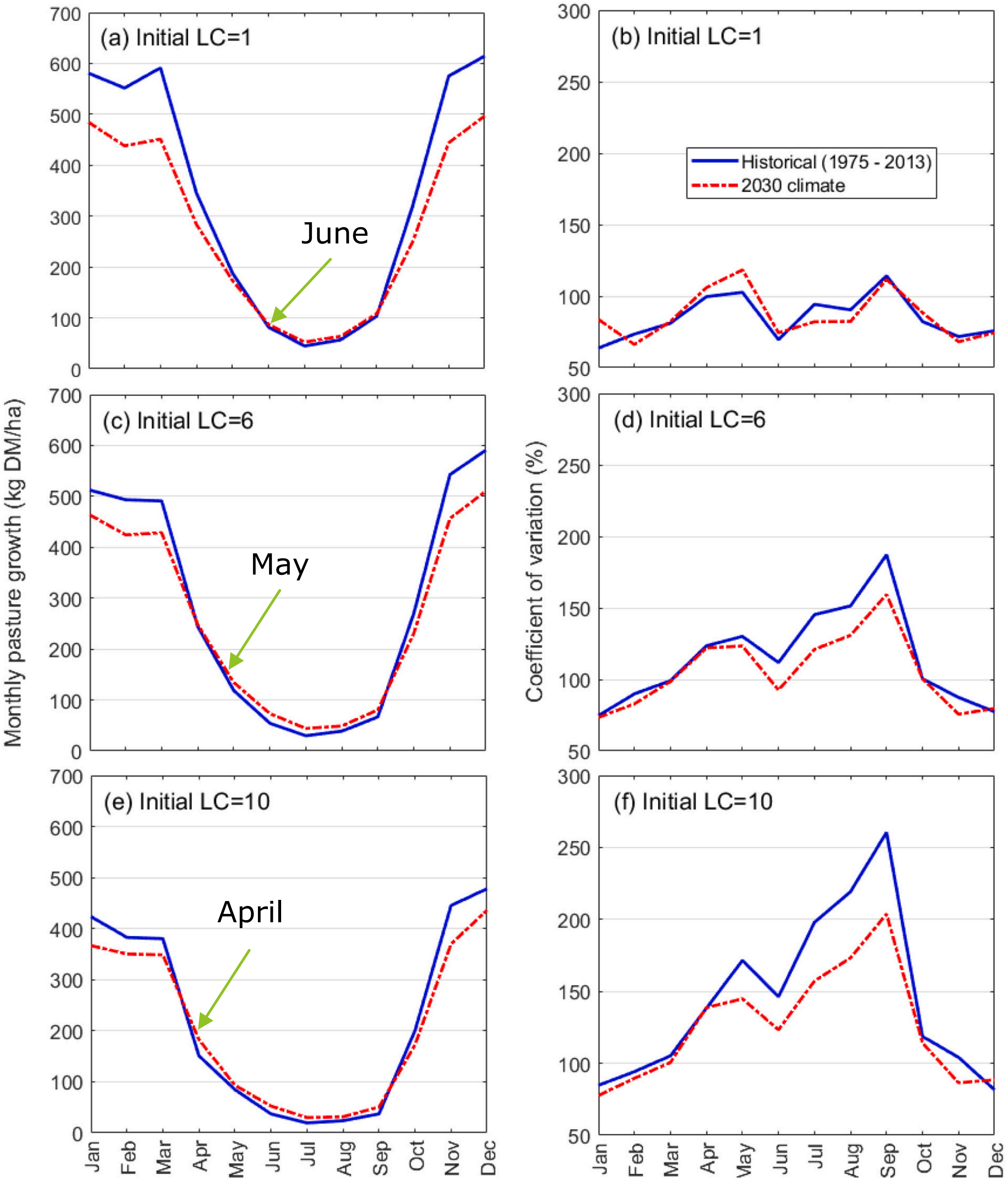

Fig. 4. Monthly pasture growth at the beef enterprise for the historical and 2030s climates for three initial land conditions (LCs) i.e. good (1; top), moderate (6; middle) and poor (10; bottom). The initial grass basal area (GBA) was set at 3% in all three cases. Through the feedback simulations, pasture growth rate is driven by not only weather but also stocking rate, land condition and GBA.

Table 4
Annual pasture growths in the historical and 2030s climate with three initial land conditions. The initial GBA was set at 3% in the three cases.

Initial land condition	Average annual pasture growth (kg ha^{-1})		Impact (% change)
	Historical climate	2030s Climate	
Good	4047	3296	−19
Moderate	3451	3126	−9
Poor	2669	2485	−7

would be reduced by approximately 10% to an average 270 tons as compared an average 300 tons in the historical climate.

Here, the combined effect of reduced animal density and better pasture growth both occurring in the warmer winter was the driver of increased animal LWG not only in winter but annually. There were two mechanisms for this i.e., a direct mechanism and a carry-over mechanism. In the former, more available pasture and smaller animal density in winter would reduce the risk of losing animal weight due to intake at below the maintenance energy level (ME_m, Fig. S3). This winter risk of the historical (baseline) climate was critical in northern Australia and

Table 5

Animal number (i.e., herd size) of the beef enterprise for the historical and 2030s climates at three initial land conditions, i.e., good, moderate and poor. The initial GBA was set at 3% in the three cases.

Initial land condition	Average animal number			Coefficient of variation (%)	
	Historical climate	2030s climate	Impact (% change)	Historical climate	2030s climate
Good	3307	2824	−15	7.5	10.5
Moderate	3111	2744	−12	11.1	11.7
Poor	2903	2580	−11	13.6	15.4

more notable with worse land conditions (Fig. 6). The rate of weight loss in animal due to intake being below ME_m is greater than the rate of weight gain when intake is greater than ME_m ($k_m > k_g$, Fig. S3), especially if a pregnancy or lactation demand is also required. The 2030s climate thus directly reduced the winter risk of losing animal weight by providing better winter intake. This direct mechanism was clearer with worse land conditions (Fig. 6(b) and (c)) than with the good land condition (Fig. 6(a)). The better winter intake also helped animals be ready to grow when the growing season came rather an initial recovery phase and then a delayed growth phase in the baseline climate. This is what we have referred to as the carry-over mechanism, explaining why better animal LWG could be achieved after the winter (in September and October, Fig. 6).

3.3.3. Livestock emissions and profitability

The 2030s climate exhibits a reduction in monthly livestock emissions of 15%, 10% and 9%, respectively, with good, moderate and poor initial land conditions (Table 7) due to smaller optimal sustainable herd sizes (OSHSs). The emission intensities, however, were relatively similar between historical climate (0.42 $kgCO_2$/kg beef sold) and 2030s climate (0.43 $kgCO_2$/kg beef sold).

Smaller OSHSs also reduced average annual gross margins in the 2030s climate which were lower than those in the historical climate by \$66 k (−13%), \$47 k (−6%), and \$6 k (−2%), respectively, for good, moderate, and poor initial land conditions (Table 8). As a result, the future profitability of the land resource declined to an average \$45 per ha compared to an average \$49 per ha in the historical climate.

4. Discussion

The focus of this study is on the impact of climate change on the seasonal production of the feed base and its translation to herd dynamics, animal productivity (per head) and production (per hectare), enterprise profit and emissions, and the feedback interactions associated with animal numbers (herd size, stocking rate) and land condition. Direct impacts of climate change on cattle are areas of ongoing research and development. A warmer climate tends to increase water demand among cattle, and increase both cattle heat stress (Henry et al., 2012; Chang-Fung-Martel et al., 2017), and the vulnerability of cattle to disease and parasites (Sutherst, 2001), while reducing pasture quality (Minson and McDonald, 1987).

Our whole-of-farm feedback simulations (in CLEM) provide, for the first time, a detailed climate change impact assessment of the performance of individual cattle for an enterprise in central Queensland.

The results in generally consistent with other simulations and empirical studies in northern Australia. Cobon et al. (2020) conducted GRASP simulations for 171 sites and estimated the average percentage change in annual pasture productivity for all of Queensland as–21% and–2%, respectively, for a given rainfall and temperature response to a future climate change scenario $(\Delta T, \Delta R)$of (0 °C,–20%) and (3 °C, 0%) where the first figure in the brackets$\Delta T$are the projected temperature change and the second figures are theΔR the projected rainfall changes. Our new results lie within the ranges given by Cobon et al. (2020).

We also examined the impact of initial land conditions, projected changes in the seasonal climate, and the projected frequency and intensity of extreme events, and feedback interaction. We found that the improved animal liveweight gains are within the range(−3%, 8%) found by a different liveweight gain model based on an empirical regression method in Cobon et al. (2020) for future climate change scenarios of (0 °C,–10%) and (3 °C, 0%), respectively. Godde et al. (2019) through a system dynamic approach in northern Queensland also found that decreases in the mean rainfall and higher rainfall variability reduced herd sizes. Our biological and financial results for the baseline historical climate are also comparable to those found by Ash et al. (2015) for a northern Queensland representative enterprise (Table 9). This enterprise has a land area of 33,000 ha while the present enterprise is 8800 ha, reflecting the large difference in methane emissions (kg CO_2e/ha/year).

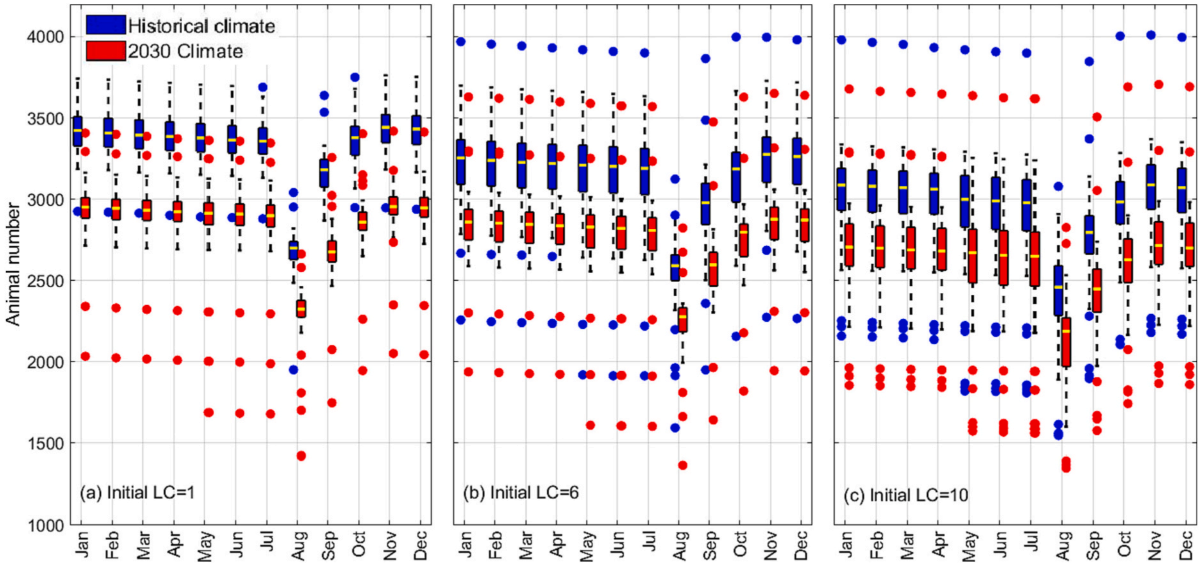

Fig. 5. Monthly total animal numbers in herds for the historical climate and 2030s climate at three initial land conditions (LCs): good (1; left), moderate (6; middle) and poor (10; right). The initial GBA was set at 3% in the three cases.

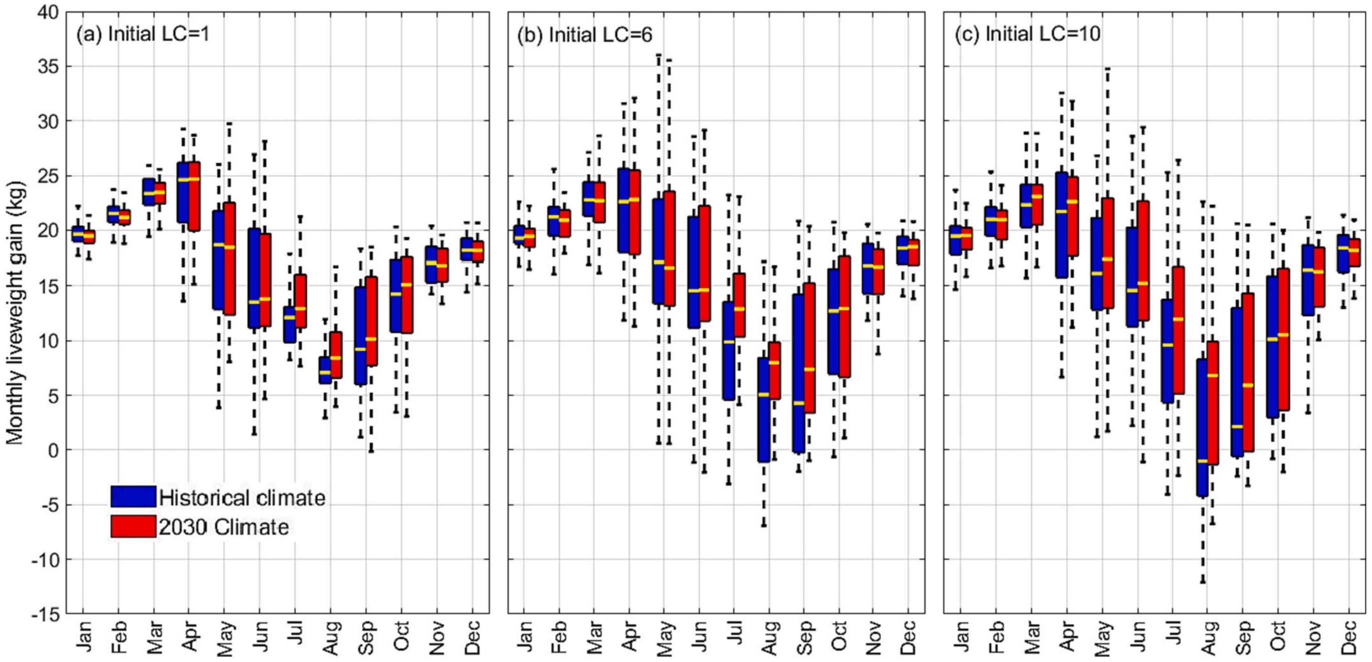

Fig. 6. Monthly weight gains of the steers (males up to 24 months) for the historical climate and 2030s climate at three initial land conditions (LCs): good (1; left), moderate (6; middle) and poor (10; right). The initial GBA was set at 3% in the three cases.

Table 6
Annual weight gains of the steers (males up to 24 months) for the historical climate and 2030s climate at three initial land conditions. The initial GBA was set at 3% in the three cases.

Initial land condition (index)	Average annual weight gain (kg/head)		Impact (% change)
	Historical climate	2030s Climate	
Good (1)	124	126	2
Moderate (6)	114	117	3
Poor (10)	105	110	5

Table 7
Monthly emissions of the beef enterprise in the historical climate and 2030s climate at three initial land conditions. The initial GBA was set at 3% in all three cases.

Initial land condition	Monthly average (tCO2e)		Impact (% change)
	Historical climate	2030s Climate	
Good	12.53	10.71	−15
Moderate	11.42	10.24	−10
Poor	10.38	9.46	−9

4.1. Effects of rainfall uncertainty and elevated CO_2 concentrations

The impact of changing rainfall on pasture is complex, depending on its surrounding environment (wooded or cleared), and if growth is water or nitrogen limited (Webb et al., 2012). Future precipitation changes are likely to influence pasture production more than the stocking method (Hall et al., 2014). Pasture growth rate responds positively to the elevated CO_2 concentration (Cullen et al., 2008; Cobon et al., 2020) owing to its effects on plant photosynthesis, nitrogen and canopy conductance (Long et al., 2004). In this study, pasture parameters affected by CO_2 concentration were calibrated according to the current ambient level of atmospheric CO_2 concentration in both the historical and 2030s climates. It is likely that higher CO_2 concentration might have positive effects on pasture growth in the wetter 2030s climate of the low impact scenario (Fig. 3), leading to higher liveweight gains, particularly in winter. This idea, however, needs further investigation.

Table 8
Average annual gross margin of the beef enterprise in the historical and 2030s climates at three initial land conditions. The initial GBA was set at 3% in all three cases.

Initial land condition	Average annual gross margin (GM) of the beef enterprise (AUDk)		Impact (% change)
	Historical climate	2030s climate	
Good	507	441	−13
Moderate	426	401	−6
Poor	362	356	−2

While we found reductions in the pasture production due to a reduction in rainfall, we are, however, cautious about future rainfall projections. Higher and lower rainfall compared to what we studied here is possible and should be considered together with an elevated CO_2 concentration. Cobon et al. (2020) showed that if future rainfall increases by 10% with a CO_2 concentration at 700 ppm, a 30% increase in QLD pasture production can be achieved. Increased pasture production in winter is important for livestock productivity, however we estimate a lower annual production in the 2030s climate due to lower annual pasture production and lower herd size needed to maintain the land condition.

4.2. Future efforts

In this study, we showed that a warmer future climate might lift pasture productivity in winter, increasing cattle liveweight gain substantially in winter and spring for production systems where winter is the critical period of feed shortage across northern Australia.

Improved pasture growth in winter was also found in other studies for grazing systems in southern Australia (Cullen et al., 2008; Moore and Ghahramani, 2013; Harrison et al., 2017) and Queensland (Cobon et al., 2020). However, improved pasture growth effects on animal liveweight are yet to be comprehensively quantified and explained. In northern Australia where summer is the main growing season, winter is a critical

Table 9

Average annual biological and financial results for the baseline historical climate with moderate initial land condition. Results by Ash et al. (2015) were from a modelled case study in Townsville (the northern Queensland representative enterprise) for the simulation period of 1985–2010.

	Ash et al. (2015)	This study	Regional average
Herd size (AEs)	2901	2532	
Weaning rate (%)	58	62	61 (Holmes, 2011), 62 (McGowan et al., 2014)
Growth rate (kg/head/year)	127	115*	
Beef turned off (kg)	331,091	297,959	
Methane (kg CO_2e/ha/year)	205	697	
Methane intensity (kg CO_2e/kg beef produced)	18.7	15	
Pasture utilisation (%)	27	26**	
Gross margin ($/AE)	125	166	152 (Holmes, 2011)

* Only for steers.

** This estimation is the average in June over all years (1975–2013).

period of limited pasture growth typically being associated with negative liveweight gains. A small improvement in winter pasture growth is therefore of significance as demonstrated for our Central Queensland beef enterprise. It is likely that better pasture growth in winter might apply for the whole beef production sector of northern Australia. This indicates the need for a large-scale study in northern Australia to determine the extent of increased lightweight gains, including the positive effects of elevated CO_2 concentration, but with reduced sustainable herd sizes in the future climate. We also need a large-scale study on the effects of warmer future climate on global grazing systems. These large-scale studies haven't been possible due mainly to the limitation in modelling capability at the livestock enterprise level and an efficient coupling mechanism with locally validated pasture production databases.

4.3. Incremental vs transformative adaptation

By altering a significant component of the biophysical environment, climate change is placing an adaptation challenge on global grazing-based production systems given the current patterns of land use and management. Changes in adaptation are required to cope with both an increased incidence of extreme weather events and change in long-term mean conditions (Rivington et al., 2007; Harrison et al., 2017). Climate change impacts are often specific to local conditions, meaning adaptation options need to be developed in a way that are context- and application-specific (Cullen et al., 2021). Incremental adaptation of current management systems such as increasing soil fertility, adaptive pasture species and animal genetic improvement are potential options but they become less effective with larger or more rapid changes to the climate (Ghahramani and Moore, 2015). In such cases, more transformational changes in resource allocation need to be considered, such as radical land use change including changing location to access more favourable climatic regions, diversification of production systems and livelihoods (Howden et al., 2007; Tran et al., 2022).

In the present study, we found that the 2030s climate will likely cause increased drought sensitivity of the enterprise due to rainfall reduction with more dry days and longer dry spells. In terms of herd dynamics (animal number), we demonstrated that better land conditions are more resilient to drought in the baseline climate but not the case in the 2030s climate due to the increased risk of large reductions in the herd size. This is likely a result of climate change impacts on pasture biomass productivity where the good land condition showed the greatest biomass productivity decrease in the 2030s climate. There were smaller decreases in pasture biomass productivity when there was less pasture growth and grass basal area where poorer land conditions were parameterised to reflect a greater proportion of annual grass species. However, future climate might not change the livestock emission intensity and net-zero emission remains a challenge. Furthermore, despite the estimated better liveweight gain of animals that can be achieved in winter due to warmer conditions elevating pasture growth and extending the growing season, there will likely be a reduction in the annual production of pasture by 2030s. This will lead to the reduction of the sustainable herd size, reducing beef production per financial year, the annual income and the profitability of the land resources (gross margin per ha). More adaptation options and pathways are required which will require changes to production systems. We need to address the adaptation challenge through a transdisciplinary research approach (Klenk and Meehan, 2015; Cullen et al., 2021), integrating knowledge from different disciplines and combining farmer knowledge with farm systems and economic analysis as well as social understanding regarding the drivers of change.

4.4. Limitations

While important to understand the climate change impact in traditional timespans such as in 2050s and further, there is a stronger demand from stakeholders including farmers or farm managers in understanding impacts in a near future such as the 2030s climate, responding to the changes currently observed and fostering their immediate actions. We thus concentrate on the 2030s climate in this study. We also acknowledge that climate variability in eastern Australia is high and there is real uncertainty in trying to parameterise the model for theoretical 2050s conditions.

Grazing production systems in northern Australia are complex systems which involve pasture and animal production, herd management, economics, emissions, and the interactions among these things. While the presently developed whole-of-farm model aiming to satisfactorily represent these factors and their interactions, it has limitations as a modelling approach and inherited shortcomings from its component models such as those of GRASP and CLEM. We note that CLEM is currently under active development to meet diverse modelling requirements from users.

The used CLEM currently cannot assess the direct impacts of climate change on animal such as the heat stress on cattle or on reproductive performance of the cows, which are areas of ongoing research and development in the model. All the climate change impacts on the studied beef enterprise were derived from the effects of climate change on the forage base (grass growth and production) and their translation into the cattle herd through feeding and management and the feedback interaction between herd dynamics and pasture growth. Interactions such as how the enterprise emissions are changing regarding different herd management operations require further model development. We then can model, for example, if the enterprise carbon footprint can be reduced by more forage in winter and greater weight gains helping steers reach market weight sooner. We also note that some of our findings might be specific to the modelled enterprise system – a self-replacement breeding herd solely on self-produced pasture – and studied geographical region in the present work. In other parts of the world or enterprises, steers might not finish on grass but on feedlot operations, farm managers can buy weaners, and feed supplements are provided routinely.

5. Conclusion

We conducted the first holistic and benchmark study on climate change impacts at the enterprise level in Central Queensland which included feedbacks on livestock production associated with land condition. The modelling challenge was how to robustly quantify the climate change impacts on the studied beef enterprise of the 2030s climate over the baseline period because the impacts might be small and indistinguishable from interannual variability in certain systems. We addressed that challenge for the northern Australia beef cattle production systems by the proposed and developed coupling method between grass and animal dynamics, allowing to account the feedback of herd dynamics on the grass growth that we hypothesise is the driving factors of this system.

The findings have implications for beef production in subtropical/tropical pastoral systems. For the projected 2030s climate that best matches the recent observed trends at the studied region, we estimate a reduction in monthly rainfall by around 10% and an increase in monthly temperature by 1 °C around 2030s. The rainfall reduction and temperature increase in the 2030s climate will reduce pasture growth in spring and summer but increase pasture growth in winter and autumn. The increased pasture growth in winter and autumn cannot compensate for the reduction in pasture growth in other seasons but can improve animal weight gain in winter and spring, increasing the annual weight gain of selling steers which has implications for income of the beef enterprise. These outcomes were previously unknown without detailed biophysical modelling.

Despite the better liveweight gain, we have shown that under the warmer and drier 2030s climate scenario considered, there will likely be a negative impact on overall beef production and profits under all initial land conditions because of a reduction in the sustainable herd size to avoid deteriorating the land condition. The same 2030s climate scenario will likely see a reduction in annual beef production as well as the economic viability of the available resources (gross margin per ha). While the emission intensity in the 2030s climate considered will remain stable, an increased drought sensitivity of the enterprise due to rainfall reduction with more dry days and longer dry spells is projected. In terms of herd dynamics (animal number), we demonstrated that better land conditions are more resilient to drought in the baseline climate but not the case in the 2030s climate due to the increased risk of large reductions in the herd size. This is a result of climate change impacts on pasture biomass productivity where the good land condition showed the greatest biomass productivity decrease in the 2030s climate.

CRediT authorship contribution statement

Duc-Anh An-Vo: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **David Cobon:** Data curation, Formal analysis, Funding acquisition, Investigation, Project administration, Resources. **Jo Owens:** Methodology, Software, Validation. **Adam Liedloff:** Conceptualization, Investigation, Software, Validation. **Tim Cowan:** Validation, Writing – review & editing. **Scott Power:** Validation, Writing – review & editing.

Declaration of Competing Interest

Duc-Anh An-Vo reports financial support was provided by Meat and Livestock Australia. David Cobon reports financial support was provided by Queensland Government.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103838.

References

Ash, A., Hunt, L., McDonald, C., Scanlan, J., Bell, L., Cowley, R., et al., 2015. Boosting the productivity and profitability of northern Australian beef enterprises: exploring innovation options using simulation modelling and systems analysis. Agr. Syst. 139, 50–65.

Bowen, M.K., Chudleigh, F., 2018. Fitzroy Beef Production Systems: Preparing for, Responding to, and Recovering from Drought.

Brás, T.A., Seixas, J., Carvalhais, N., Jägermeyr, J., 2021. Severity of drought and heatwave crop losses tripled over the last five decades in Europe. Environ. Res. Lett. 16 (6), 065012.

Cacho, O.J., Bywater, A.C., Dillon, J.L., 1999. Assessment of production risk in grazing models. Agr. Syst. 60 (2), 87–98.

Chang-Fung-Martel, J., Harrison, M.T., Rawnsley, R., Smith, A.P., Meinke, H., 2017. The impact of extreme climatic events on pasture-based dairy systems: a review. Crop and Pasture Science 68 (12), 1158–1169.

Cobon, D.H., Stone, G., Carter, J., McKeon, G., Zhang, B., Heidemann, H., 2020. Native pastures and beef cattle show a spatially variable response to a changing climate in Queensland, Australia. European Journal of Agronomy 114, 126002.

CSIRO, 2022. Climate Change in Australia Web Portal. https://www.climatechangeinaustralia.gov.au/en/projections-tools/summary-data-explorer/.

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

Cullen, B., Eckard, R., Johnson, I., Lodge, G., Walker, R., Rawnsley, R.P., Perring, M., et al., 2008. Climate change impacts on Australian grazing systems. In: Whole Farm Systems Analysis and Tools for the Australian and New Zealand Grazing Industries Project Report.

Cullen, B.R., Ayre, M., Reichelt, N., Nettle, R.A., Hayman, G., Armstrong, D.P., Harrison, M.T., et al., 2021. Climate change adaptation for livestock production in southern Australia: transdisciplinary approaches for integrated solutions. Anim. Front. 11 (5), 30–39.

Dalal, Ram C., Thornton, Craig M., Allen, Diane E., Owens, Jo S., Kopittke, Peter M., 2021. Long-term land use change in Australia from native forest decreases all fractions of soil organic carbon, including resistant organic carbon, for cropping but not sown pasture. Agric. Ecosyst. Environ. 311 (107326), 107326 https://doi.org/10.1016/j.agee.2021.107326.

Day, K.A., McKeon, G.M., Carter, J.O., 1997. Evaluating the Risk of Pasture and Land Degradation in Native Pastures in Queensland, Final Report on DAQ124A to RIRDC (Six Volumes).

Fariña, S.R., Alford, A., Garcia, S.C., Fulkerson, W.J., 2013. An integrated assessment of business risk for pasture-based dairy farm systems intensification. Agr. Syst. 115, 10–20.

Foran, B.D., Smith, D.S., Niethe, G., Stockwell, T., Michell, V., 1990. A comparison of development options on a northern Australian beef property. Agr. Syst. 34 (1), 77–102.

Ghahramani, A., Moore, A.D., 2015. Systemic adaptations to climate change in southern Australian grasslands and livestock: production, profitability, methane emission and ecosystem function. Agr. Syst. 133, 158–166.

Godde, C., Dizyee, K., Ash, A., Thornton, P., Sloat, L., Roura, E., et al., 2019. Climate change and variability impacts on grazing herds: insights from a system dynamics approach for semi-arid Australian rangelands. Glob. Chang. Biol. 25 (9), 3091–3109.

Grose, M.R., Narsey, S., Delage, F.P., Dowdy, A.J., Bador, M., Boschat, G., et al., 2020. Insights from CMIP6 for Australia's future climate. Earth's Future 8 (5) (e2019EF001469).

Harrison, M.T., Cullen, B.R., Rawnsley, R.P., 2016. Modelling the sensitivity of agricultural systems to climate change and extreme climatic events. Agr. Syst. 148, 135–148.

Hall, T.J., McIvor, J.G., Reid, D.J., Jones, P., MacLeod, N.D., McDonald, C.K., Smith, D. R., 2014. A comparison of stocking methods for beef production in northern Australia: pasture and soil surface condition responses. Rangel. J. 36 (2), 161–174.

Harrison, M.T., Cullen, B.R., Armstrong, D., 2017. Management options for dairy farms under climate change: effects of intensification, adaptation and simplification on pastures, milk production and profitability. Agr. Syst. 155, 19–32.

Heidemann, H., Cowan, T., Henley, B.J., Ribbe, J., Freund, M., Power, S., 2023. Variability and long-term change in Australian monsoon rainfall: a review. Wiley Interdiscip. Rev. Clim. Chang. 14 (3), e823.

Henry, B., Charmley, E., Eckard, R., Gaughan, J.B., Hegarty, R., 2012. Livestock production in a changing climate: adaptation and mitigation research in Australia. Crop and Pasture Science 63 (3), 191–202.

Holmes, W.E., 2011. Representative Herd Templates for Northern Australia V1.00 — Data Files for Breedcow and Dynama Herd Budgeting Software, Beef CRC, DEEDI (Qld), DAFWA and DRDPIF&R (NT) viewed on 04 November 2022. at. http://www.daff.qld.gov.au/16_20534.htm.

Howden, S.M., Soussana, J.F., Tubiello, F.N., Chhetri, N., Dunlop, M., Meinke, H., 2007. Adapting agriculture to climate change. Proc. Natl. Acad. Sci. 104 (50), 19691–19696.

IPCC, 2021. https://www.ipcc.ch/report/ar6/wg1/downloads/factsheets/IPCC_AR6_WGI_Regional_Fact_Sheet_Australasia.pdf.

Kirtman, B., Power, S.B., Adedoyin, A.J., Boer, G.J., Bojariu, R., Camilloni, I., et al., 2013. Near-term climate change: projections and predictability. Climate Change 2013: The physical science basis. In: IPCC Working Group I Contribution to AR5., pp. 953–1028.

Klenk, N., Meehan, K., 2015. Climate change and transdisciplinary science: problematizing the integration imperative. Environ. Sci. Policy 54, 160–167.

Laing, A., Liedloff, A., 2023. CLEM User Guide and Reference Manual. CSIRO Agriculture and Food accessed 09 November 2023. https://www.apsim.info/clem/Content/Home.htm.

Lee, J.Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J.P., et al., 2021. Future global climate: Scenario-based projections and near-term information. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp. 553–672.

Long, S.P., Ainsworth, E.A., Rogers, A., Ort, D.R., 2004. Rising atmospheric carbon dioxide: plants FACE the future. Annu. Rev. Plant Biol. 55, 591–628.

McCown, R.L., 1981. The climatic potential for beef cattle production in tropical Australia: part I—simulating the annual cycle of liveweight change. Agr. Syst. 6 (4), 303–317.

McGowan, M., Fordyce, G., O'Rourke, P., Barnes, T., Morton, J., Menzies, D., Jephcott, S., McCosker, K., Smith, D., Perkins, N., Marquart, L., Newsome, T., Burns, B., 2014. Northern Australian Beef Fertility Project: CashCow. Final Report Project B.NBP.0382. Meat & Livestock Australia Limited, North Sydney (ISBN: 9781925045840).

McKeon, G., Ash, A., Hall, W., Smith, M.S., 2000. Simulation of grazing strategies for beef production in north-East Queensland. Applications of seasonal climate forecasting in agricultural and natural ecosystems 227–252.

McKeon, G.M., Stone, G.S., Syktus, J.I., Carter, J.O., Flood, N.R., Ahrens, D.G., et al., 2009. Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of issues. The Rangeland Journal 31 (1), 1–29.

Minson, D.J., McDonald, C.K., 1987. Estimating forage intake from the growth of beef cattle. Tropical Grasslands 21 (3), 116–122.

MLA, 2022. Global Beef Industry and Trade Report.

Moore, A.D., Ghahramani, A., 2013. Climate change and broadacre livestock production across southern Australia. 1. Impacts of climate change on pasture and livestock productivity, and on sustainable levels of profitability. Glob. Chang. Biol. 19 (5), 1440–1455.

Rickert, K.G., Stuth, J.W., McKeon, G.M., 2000. In: Mannetje, L.T., Jones, R.M. (Eds.), Modelling Pasture and Animal Production. Field and Laboratory Methods for Grassland and Animal Production Research. CAB International, pp. 29–66.

Rivington, M., Matthews, K.B., Bellocchi, G., Buchan, K., Stöckle, C.O., Donatelli, M., 2007. An integrated assessment approach to conduct analyses of climate change impacts on whole-farm systems. Environ. Model. Software 22 (2), 202–210.

Scanlan, J.C., MacLeod, N.D., O'Reagain, P.J., 2013. Scaling results up from a plot and paddock scale to a property–a case study from a long-term grazing experiment in northern Australia. The Rangeland Journal 35 (2), 193–200.

Scanlan, J.C., McIvor, J.G., Bray, S.G., Cowley, R.A., Hunt, L.P., Pahl, L.I., et al., 2014. Resting pastures to improve land condition in northern Australia: guidelines based on the literature and simulation modelling. The Rangeland Journal 36 (5), 429–443.

Smith, J.B., Hans-Joachim, S., Monirul Qader Mirza, M., Fankhauser, S., Leemans, R., Erda, L., Ogallo, L., Pittock, B., Richels, R., Rosenzweig, C., Safriel, U., Tol, R.S.J., Weyant, J., Yohe, G., Bond, W., Bruckner, T., Iglesias, A., McMichael, A.J., Parmesan, C., Price, J., Rahmstorf, S., Root, T., Wigley, T., Zickfeld, K., 2001. Chapter 19: Vulnerability to climate change and reasons for concern: A synthesis. In: McCarthy, J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.), Climate Change 2001: Impacts, Adaptation, and Vulnerability Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK (Available: http://www.ipcc.ch/ipccreports/tar/wg2/index.php?idp= 680#19631).

Sutherst, R.W., 2001. The vulnerability of animal and human health to parasites under global change. Int. J. Parasitol. 31 (9), 933–948.

Teague, W.R., Foy, J.K., 2002. Validation of SPUR2. 4 rangeland simulation model using a cow-calf field experiment. Agr. Syst. 74 (2), 287–302.

Tess, M.W., Kolstad, B.W., 2000. Simulation of cow-calf production systems in a range environment: I. Model development. J. Anim. Sci. 78 (5), 1159–1169.

Thompson, T., Martin, P., 2014. Australian beef: financial performance of beef cattle producing farms, 2011-12 to 2013-14. In: ABARES Research Report, (14.07).

Tran, V.T., An-Vo, D.A., Mushtaq, S., Cockfield, G., 2022. Nuanced assessment of livelihood resilience through the intersectional lens of gender and ethnicity: evidence from small-scale farming communities in the upland regions of Vietnam. J. Rural. Stud. 92, 68–78.

Webb, N.P., Stokes, C.J., Scanlan, J.C., 2012. Interacting effects of vegetation, soils and management on the sensitivity of Australian savanna rangelands to climate change. Clim. Change 112 (3–4), 925–943.

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Corrigendum

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