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Influence of climate variability and stocking strategies on greenhouse gas emissions (GHGE), production and profit of a northern Queensland beef cattle herd

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Abstract. Previous studies of greenhouse gas emissions (GHGE) from beef production systems in northern Australia have been based on models of 'steady-state' herd structures that do not take into account the considerable inter-annual variation in liveweight gain, reproduction and mortality rates that occurs due to seasonal conditions. Nor do they consider the implications of flexible stocking strategies designed to adapt these production systems to the highly variable climate. The aim of the present study was to quantify the variation in total GHGE (t CO_2e) and GHGE intensity (t CO_2e/t liveweight sold) for the beef industry in northern Australia when variability in these factors was considered. A combined GRASP–Enterprise modelling platform was used to simulate a breeding–finishing beef cattle property in the Burdekin River region of northern Queensland, using historical climate data from 1982–2011. GHGE was calculated using the method of Australian National Greenhouse Gas Inventory. Five different stocking-rate strategies were simulated with fixed stocking strategies at moderate and high rates, and three flexible stocking strategies where the stocking rate was adjusted annually by up to 5%, 10% or 20%, according to pasture available at the end of the growing season. Variation in total annual GHGE was lowest in the 'fixed moderate' (~9.5 ha/adult equivalent (AE)) stocking strategy, ranging from 3799 to 4471 t CO_2e, and highest in the 'fixed high' strategy (~5.9 ha/AE), which ranged from 3771 to 7636 t CO_2e. The 'fixed moderate' strategy had the least variation in GHGE intensity (15.7–19.4 t CO_2e/t liveweight sold), while the 'flexible 20' strategy (up to 20% annual change in AE) had the largest range (10.5–40.8 t CO_2e/t liveweight sold). Across the five stocking strategies, the 'fixed moderate' stocking-rate strategy had the highest simulated perennial grass percentage and pasture growth, highest average rate of liveweight gain (121 kg/steer), highest average branding percentage (74%) and lowest average breeding-cow mortality rate (3.9%), resulting in the lowest average GHGE intensity (16.9 t CO_2e/t liveweight sold). The 'fixed high' stocking rate strategy (~5.9 ha/AE) performed the poorest in each of these measures, while the three flexible stocking strategies were intermediate. The 'fixed moderate' stocking strategy also yielded the highest average gross margin per AE carried and per hectare. These results highlight the importance of considering the influence of climate variability on stocking-rate management strategies and herd performance when estimating GHGE. The results also support a body of previous work that has recommended the adoption of moderate stocking strategies to enhance the profitability and ecological stability of beef production systems in northern Australia.

Additional keywords: reproduction; mortality rate; mitigation.

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Introduction

Beef cattle grazing predominantly native grasses and, to a lesser extent, sown perennial pastures is the dominant (~90%) economic land use of northern Australia. The northern beef herd comprises ~50% (~15 million cattle) of the national herd, with annual production valued at over AU$5 billion (MLA 2013; DIRD 2015). These cattle represent a substantial source of greenhouse gas emissions (GHGE) (Bray *et al*. 2014).

Previous studies of GHGE from beef production systems in northern Australia have been based on models of 'steady-state' herd structures, with fixed assumptions for reproduction and mortality rates, and annual rates of liveweight gain per animal (e.g. Bentley *et al*. 2008; Cullen *et al*. 2016; Harrison *et al*. 2016). However, the high dependence on low-quality forages, coupled with a highly variable climate, which is characteristic of northern Australia (McKeon *et al*. 1998), leads to considerable inter-annual variation in reproduction and mortality rates (e.g. Bortolussi *et al*. 2005*a*; Fordyce *et al*. 2013), and, hence, the numbers of animals carried on pastures, as well as in annual rates of liveweight gain (Bortolussi *et al*. 2005*b*). Thus 'steady-state' analyses cannot capture the range of outcomes expected across seasons.

The scale of grazing holdings in northern Australia is typically large (20 000–300 000 ha). While levels of farming inputs are low by comparison to temperate grazing systems, animal productivity is constrained by highly variable rainfall and soil-fertility limitations (O'Reagain and Scanlan 2013). Rainfall variations can cause annual pasture production to fluctuate by five- or six-fold, creating management challenges to maintain suitable stocking rates. One approach to coping with this climate variability is to use a fixed stocking rate to suit an average rainfall year, but this strategy may result in lost grazing opportunities in good seasons (Stafford Smith 1996) and in overgrazing, land degradation and economic loss during drought years (O'Reagain *et al*. 2011). Alternatively, increasing and reducing stocking rates during good and poor rainfall years in a reactive manner may also lead to overgrazing if animal numbers are not adjusted quickly enough to prevent damage to pastures and soils (McKeon *et al*. 2004).

Flexible stocking-rate strategies have been recommended for northern grazing systems to more sustainably manage herds under both good and poor seasonal conditions (e.g. Wilson and MacLeod 1991; Hunt 2008; McIvor 2012; Pahl *et al*. 2013). A common suggestion is for stock numbers to be varied at the end of the pasture growing season to suit the total available pasture standing dry matter, offering greater protection to species composition and land condition during poor years (Johnston *et al*. 1996; O'Reagain and Scanlan 2013). Since GHGE are largely driven by animal numbers (Browne *et al*. 2011), a flexible stocking-rate strategy where the number of cows in the breeding herd and numbers of livestock sold change with de-stocking and re-stocking cycles, will have significant implications for GHGE. The aim of the present study was to quantify the variation in total GHGE and GHGE intensity for northern Australian beef enterprises when variation in reproduction and mortality rates, rates of animal liveweight gain and stocking strategies in response to seasonal conditions were taken into account. So as to further understand the implications of the stocking strategies for farm performance, the annual gross margin was determined. A case-study breeding–finishing beef property located in the Burdekin River region of northern Queensland was modelled using five different stocking-rate strategies.

Materials and methods

Modelling approach

Bioeconomic simulation modelling was applied to a synthetic case-study beef breeding–finishing property in the Burdekin River region of northern Queensland, Australia, to quantify annual liveweight production, gross margin and GHGE under five stocking-rate strategies across a range of seasonal conditions (described below). This was achieved by linking a biophysical pasture and animal growth model (GRASP; McKeon *et al*. 2000) with a herd economic model (Enterprise; MacLeod and Ash 2001) and Greenhouse Accounting Framework for beef (B-GAF; Browne *et al*. 2011).

The GRASP model has been used extensively in northern Australia to simulate varying stocking rates, livestock production and soil-health dynamics (Stafford Smith *et al*. 2000; McKeon *et al*. 2009; Scanlan *et al*. 2013). In the present study, GRASP was used to simulate soil-water dynamics, pasture growth, vegetation condition (basal area, perennial grass composition), herbage utilisation and steer daily liveweight gain, based on Hall *et al*. (1998). The GRASP model has been shown to accurately predict pasture mass and steer liveweight gain in beef production systems in the region (Scanlan *et al*. 2013). Enterprise models the annual structure of a herd and patterns of annual sales of steers and surplus female animals and calculates economic values (MacLeod and Ash 2001). The structural dynamics of the modelled herd are primarily driven by changes in reproduction and mortality rates, and stocking rates. For grazing systems in northern Australia, the former are largely functions of nutrition, animal growth and body condition, and the latter is the principal parameter being manipulated for the stocking strategies compared in the present study. Enterprise captures the seasonal effect on branding percentages (defined as the number of calves weaned as a percentage of the number of cows mated) and mortality rates of breeding cows through regression equations that are linked to the GRASP projections of steer annual liveweight gain using the procedure described by Scanlan *et al*. (2013). The numbers of animals in each livestock class, their weight and rate of liveweight gain from the GRASP–Enterprise modelling was then entered into B-GAF to calculate GHGE from methane and nitrous oxide, using the Australian National Greenhouse Gas Inventory method (Browne *et al*. 2011). B-GAF requires seasonal inputs of data. For steer liveweight and liveweight gain, seasonal estimates were derived from the annual liveweights of each age cohort in Enterprise and the GRASP predicted annual rate of liveweight gain, assuming a linear rate of gain through the year. For the breeding cows, liveweight averaged 400 kg through each year, but was assumed to vary from 380 to 420 kg on a seasonal basis.

Site and stocking strategies modelled

The synthetic case-study beef breeding–finishing property modelled was located ~70 km south-west of Charters Towers (20°34′S, 146°07′E) in the Burdekin River region of northern Queensland, Australia. The simulation period was from 1982 to 2011. Annual rainfall at the site largely occurs in the wet season between December and March and is highly variable, averaging 618 mm over the simulation period, but ranging from 293 to 1170 mm (Fig. 1). The land type simulated was Reid River box (*Eucalyptus brownii*) on brown sodosols and chromosols, which is common in the region (O'Reagain *et al*. 2011). The size of the property was 23 500 ha.

The property simulation was based on GRASP–Enterprise modelling previously developed by Scanlan *et al*. (2013) to place experimental data derived from the 'Wambiana' grazing trial (O'Reagain *et al*. 2011) into the context of a representative beef enterprise. A self-replacing breeding herd consisting of *Bos indicus* and *Bos indicus* × *Bos taurus* breeds was modelled with an age and sex structure typical of the region (Scanlan *et al*. 2013). The target market was for heavy export steers for northern Asia (e.g. Japan ox), with steers sold into this market if they achieved a minimum of 590 kg liveweight at 36–40 months. Steers that did not meet the target liveweight

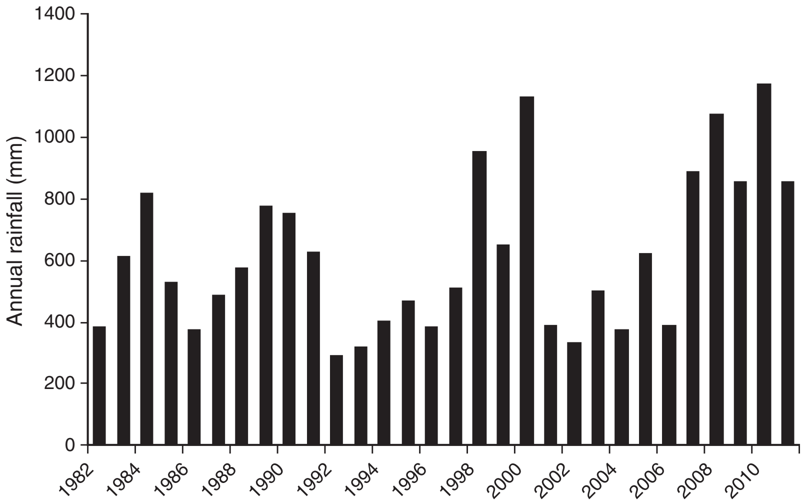

Fig. 1. Annual rainfall for the Burdekin River case-study property (1982–2011).

were sold at 40 months of age. Heifers surplus to the number required to enter the breeding herd, and steers in excess of the number required to maintain the required stocking rate (see below), were sold at an average liveweight of 235 kg. Culled cows were sold at 400 kg liveweight. Values of selected parameters used in the Enterprise model are summarised in Table 1.

In the Enterprise model, dry-season supplementary feeding of cattle was implemented when the simulated annual liveweight gain of steers fell below specified thresholds, as is common practice in northern Australia during drought (Bortolussi *et al.* 2005*c*). When projected annual liveweight gain from GRASP was between 0 and 50 kg, a dry-season supplement comprising a urea–molasses lick formulation (urea 8%, M8U) was fed to all animals to achieve a minimum annual liveweight gain of 50 kg (Tyler 1997). The feeding rule used was 2 days of M8U feeding for each kilogram of liveweight gain less than 50 kg. For example, if the liveweight gain per animal was simulated to be 10 kg, then the M8U ration was fed for 80 days. Where an annual loss in liveweight was simulated to occur, then a drought feeding supplement of urea–molasses fortified with cottonseed meal (urea 3%, cottonseed meal 10%, M3U10P) was fed, with 1 day of feeding for each 1 kg of projected weight loss. For example, if an animal was simulated to lose 20 kg over the year, then there would be 20 feeding days of M3U10P supplement and 100 days of the M8U supplement.

Table 1. Selected parameters used in the Enterprise model for the Burdekin River region case-study property

M8U, supplement comprising a urea–molasses lick formulation, with 8% urea; M3U10P, feeding supplement of urea–molasses fortified with cottonseed meal (urea 3%, cottonseed meal 38%)

Parameter	Value
Selling prices (AU$/kg liveweight basis)	
Steers – export ox (AU$)	1.75
Steers – weaners and stores (AU$)	1.50
Cows – domestic (AU$)	1.40
Cows – heifers (AU$)	1.80
Weight at 12 months of age – steers and heifers (kg liveweight)	235
Sale weights (*kg, liveweight basis*)	
Steers	590–620
Heifers	235
Cows – culled	400
Direct costs (excl. supplements) – steers/cows (AU$/head)	6.60/1.00
Supplements[A]	
Ration 1 – M8U	
Cost (AU$/day) – weaners/cows/steers	0.15/0.30/0.30
Ration 2 – M3U10P	
Cost (AU$/day) – weaners/cows/steers	0.20/0.40/0.40

[A]Subject to liveweight gain trigger.

Five stocking-rate strategies were simulated. Two were fixed stocking-rate strategies that represented contrasting stocking rates for the Burdekin region, and three were flexible strategies with varying capacity to adjust the stocking rate according to seasonal conditions. The strategies were as follows:

(1) ‘Fixed moderate’ stocking rate, with the number of cows in the breeding herd remaining at a constant size equivalent to ~9.5 ha/AE (one adult equivalent = standard livestock unit based on the feed demands of a 450-kg live non-pregnant, non-lactating cow). This strategy is consistent with recommendations of good grazing-management practice for the region (Partridge 1999).
(2) ‘Fixed high’ stocking rate, with the target number of cows in the breeding herd remaining at a constant size equivalent to ~5.9 ha/AE, corresponding to poor grazing-management practice in the region (Scanlan *et al.* 1994).
(3) Flexible stocking rate with up to a 5% change (increase/decrease) in total herd size (AE) annually, based on simulated pasture standing dry matter at the end of the growing season; hereafter termed ‘Flexible 5’.
(4) Flexible stocking rate with up to 10% change (increase/decrease) in total herd size (AE) annually, based on

simulated pasture standing dry matter at the end of the growing season; hereafter termed 'Flexible 10'.

(5) Flexible stocking rate with up to 20% change (increase/decrease) in total herd size (AE) annually, based on simulated pasture standing dry matter at the end of the growing season; hereafter, termed 'Flexible 20'.

The simulations of three flexible strategies commenced with a herd-size equivalent to the 'fixed moderate' stocking rate of 9.5 ha/AE, but then varied according to the parameters described. Annual herd stocking-rate adjustments were implemented in the Enterprise model by changing the number of breeding cows culled, and the number of heifers and steers retained on the farm according to the required stocking-rate change. It should be noted that these stocking strategies do not represent the specific experimental treatments that were conducted on the 'Wambiana' grazing trial, but are a range of strategies for herds with low, moderate and high flexibility to respond to seasonal conditions. All simulations commenced with 40% perennial grasses in the sward.

Data analyses

Data were summarised annually and used to examine overall average and inter-annual variability of a range of pasture, animal, financial and GHGE parameters for the five stocking-rate strategies. From GRASP, the key model predictions of pasture and land condition were perennial grass percentage, pasture growth (kg DM/ha), pasture utilisation percentage and water runoff (mm/year). From the Enterprise herd economic model, the annual liveweight sold (steers plus surplus females) was recorded along with the average and range of the gross margin per AE carried and per hectare over the 30 years. The number of years and the average cost of feeding when the dry-season feeding rules were invoked in a simulation were also reported. The B-GAF model reported total annual GHGE expressed as t CO_2e. GHGE intensity (t CO_2e/t liveweight sold) was calculated annually by dividing the total GHGE by total liveweight sold. No statistical analysis was applied to the model outputs because of the mechanistic, non-stochastic models being used.

Results

Liveweight gain, branding and mortality percentages, herd size and liveweight sold

Steer liveweight gain was highest and least variable for the 'fixed moderate' stocking-rate strategy (mean 121 kg/steer, range 90–130 kg/steer), and lowest and most variable for the 'fixed high' stocking-rate strategy (mean 85 kg/steer, range 40–130 kg/steer; Fig. 2*a*). The three flexible stocking strategies generated simulated liveweight gain that fell between the 'fixed moderate' and 'fixed high' stocking rates. For each of the stocking strategies, the lowest rates of liveweight gain were simulated in the years 1992–1997 and 2003.

Branding and mortality percentages of breeding cows were also highest and lowest respectively for the 'fixed moderate' stocking-rate strategy (Table 2). The 'fixed high' stocking-rate strategy had the lowest branding rate and highest mortality rate. The branding and mortality rates for the three flexible stocking policies were intermediate between the 'fixed moderate' and 'fixed high' strategies.

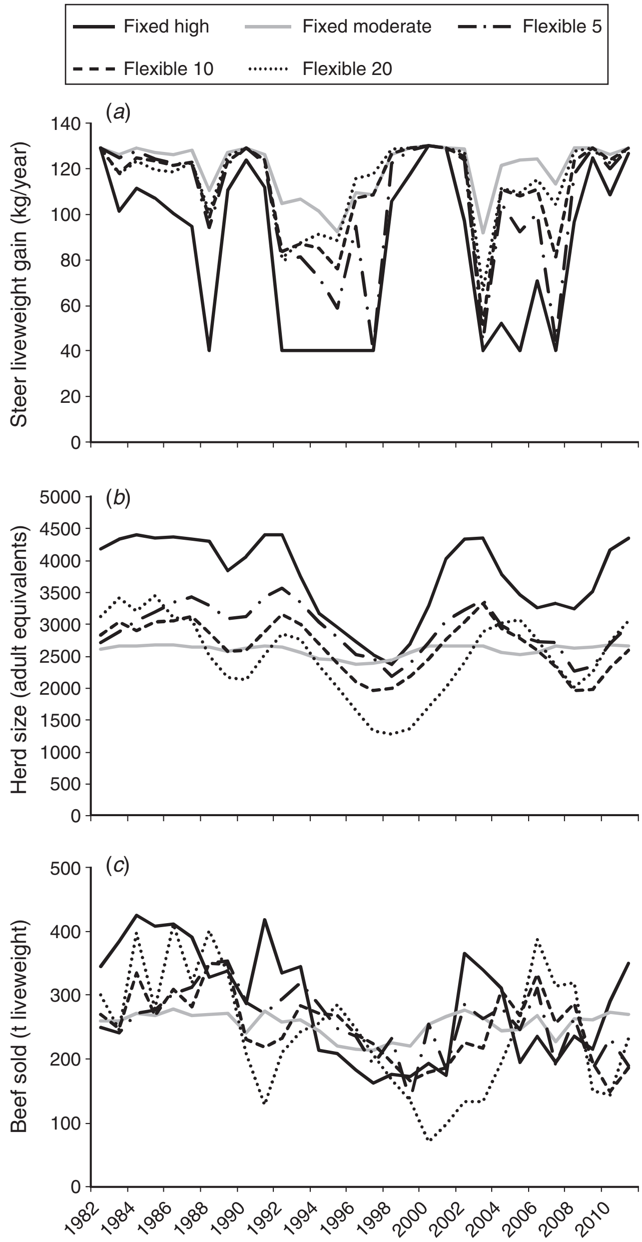

Fig. 2. Simulated annual (*a*) steer liveweight gain (kg/year), (*b*) herd size (AE) and (*c*) beef sold (t liveweight) for the Burdekin River case-study property (1982–2011) for the following five stocking strategies (see text for explanation): fixed high (——), fixed moderate (——), flexible 5 (– · –), flexible 10 (– – –) and flexible 20 (········).

Average herd size was lowest and least variable in the 'fixed moderate' strategy (average 2600 AE, range 2380–2580). The 'fixed high' strategy had the highest average herd size (3745 AE), ranging from 2370 to 4410 AE, with lower than the target AE in some years indicating that the rate of reproduction was not always sufficient to maintain the herd at a constant size. For the three flexible stocking strategies, the herd size fluctuated markedly among years, with the highest average size (2930 AE)

Table 2. Long-term average and range (in parenthesis) of simulated branding and breeding-cow mortality percentages for the five stocking-rate strategies applied to the Burdekin River case-study property (1982–2011)

See text for explanation of stocking-rate strategies

Management	Branding (%)	Breeding-cow mortality (%)
Fixed moderate	74 (60–79)	3.9 (3.7–5.0)
Fixed high	57 (35–79)	6.7 (3.7–11.1)
Flexible 5	67 (31–79)	5.0 (3.7–11.1)
Flexible 10	70 (41–79)	4.3 (3.7–8.9)
Flexible 20	72 (48–79)	4.2 (3.7–6.9)

under the 'flexible 5' strategy, due largely to the inability to reduce numbers quickly when seasonal conditions deteriorated. The average herd size was similar for the 'flexible 10' and 'flexible 20' strategies (2650 and 2490 AE respectively), but varied more widely under the 'flexible 20' simulation, ranging between 1280 and 2450 AE.

Average annual liveweight sold was highest under the 'fixed high' stocking strategy (288 t liveweight, range 162–425 t; Fig. 2*c*). The 'flexible 20' strategy had the lowest average annual liveweight sold (241 t liveweight) and the largest range (71–412 t liveweight). The other strategies gave similar average levels of liveweight sold (251–258 t liveweight). The 'fixed moderate' strategy had the smallest range in annual beef liveweight sold (213–278 t liveweight).

Pasture condition

The mean percentage of perennial grasses in the simulated pasture was higher than the starting value of 40% for both the 'fixed moderate' and the 'flexible 20' strategies, but was lower than that for the other three strategies (Table 3). The 'fixed moderate' and 'flexible 20' treatments also had higher pasture growth, lower utilisation percentages and lower simulated runoff than did the other treatments. The 'fixed high' strategy had the lowest perennial grass percentage and growth, and highest utilisation percentage and runoff, of all stocking strategies simulated.

Total GHGE and GHGE intensity

Total GHGE were highest for the 'fixed high' stocking strategy (average 6053 t CO_2e, range 3771–7636 t), while average GHGE were similar in the other stocking strategies, but the three flexible stocking strategies had higher inter-annual variability (Fig. 3*a*). For example, in the 'fixed moderate' strategy, annual GHGE ranged from 3799 to 4472 t CO_2e, while the 'flexible 20' strategy had a range of 2137–5678 t CO_2e.

Average GHGE intensity was lowest for the 'fixed moderate' stocking-rate strategy (16.9 t CO_2e/t liveweight sold) and highest for the 'fixed high' stocking-rate strategy (22.0 t CO_2e/t liveweight sold), while the three flexible strategies were intermediate between the fixed stocking strategies (Fig. 3*b*). Emissions intensity was also more variable for the flexible than the fixed stocking strategies. For example, GHG emissions intensity ranged from 10.5 to 40.8 t CO_2e/t liveweight sold in the 'flexible 20' strategy, compared with 15.7–19.4 t CO_2e/t liveweight sold in the 'fixed moderate' strategy.

Table 3. Average simulated percentage perennial grass, annual growth (kg DM/ha), runoff (mm/year) and percentage utilisation for the five stocking-rate strategies on the Burdekin River case-study property (1982–2011)

See text for explanation of stocking-rate strategies

Management	Perennial grass (%)	Growth (kg/ha.year)	Runoff (mm/year)	Utilisation (%)
Fixed moderate	58	2096	30	24
Fixed high	8	1343	74	52
Flexible 5	27	1650	57	35
Flexible 10	35	1727	51	31
Flexible 20	44	1896	40	29

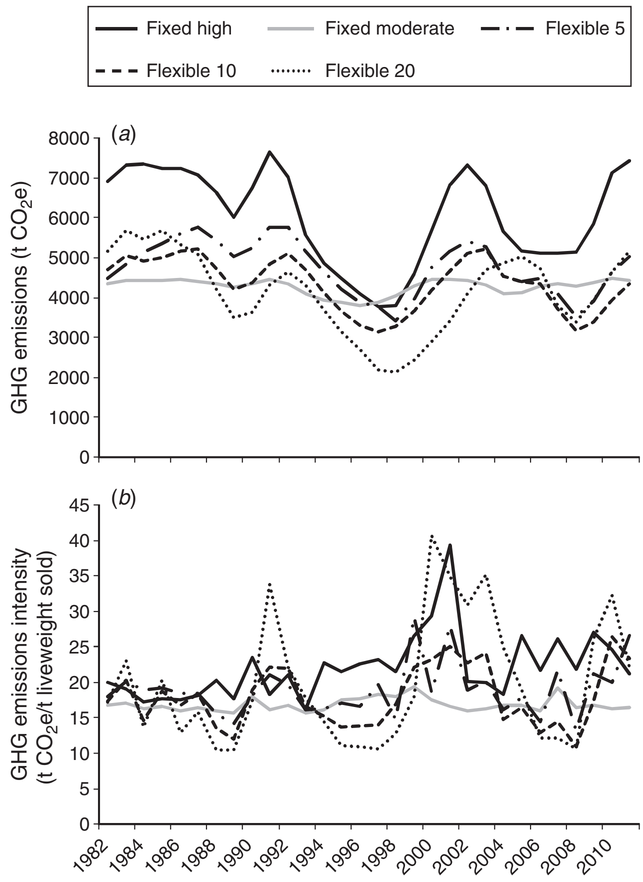

Fig. 3. Simulated (*a*) total annual greenhouse gas emissions (GHGE; t CO_2e) and (*b*) annual GHGE intensity (t CO_2e/t liveweight sold) for the Burdekin River case-study property (1982–2011) for the following five stocking strategies (see text for explanation): fixed high (——), fixed moderate (——), flexible 5 (– · –), flexible 10 (– – –) and flexible 20 (········).

Financial performance

The 'fixed moderate' stocking-rate strategy generated the highest average gross margin per AE and per hectare, as well as the highest minimum level of both measures for the

Table 4. Predicted average (range in parenthesis) gross margin/adult equivalent (AE) and gross margin/ha, percentage of years when supplementary feeding rules were invoked, and supplementary feeding costs in those year for the five stocking-rate strategies applied to the Burdekin River case-study property (1982–2011)
See text for explanation of stocking-rate strategies

Stocking-rate strategy	Fixed moderate	Fixed high	Flexible 5	Flexible 10	Flexible 20
Gross margin/AE	AU$130.95 (100.71–148.44)	AU$68.20 (–15.01–117.75	AU$103.54 (45.35–144.62)	AU$117.28 (66.61–189.09)	AU$126.00 (27.53–231.84)
Gross margin/ha	AU$13.75 (9.73–15.75)	AU$10.91 (–1.51–20.52)	AU$12.18 (4.65–18.16)	AU$12.26 (6.28–19.39)	AU$12.06 (1.90–24.65)
Years supplementary feeding rules invoked (%)	0	33	3	0	0
Supplementary feed costs in years when fed	0	AU$44963	AU$482	0	0

simulation period (Table 4). Despite having the highest number of animals carried, the 'fixed high' stocking-rate strategy yielded the lowest average gross margin per AE and per hectare, as well as the lowest minimum and maximum gross margins of any stocking strategy. It also had the highest percentage of years when supplementary feeding was required (Table 4). This result was largely due to the lower level of herd productivity (lowest liveweight gain per steer flowing to the estimates of branding rates and mortality rates), reducing the number of surplus female animals for sale and the need to incur supplementary feeding costs (both M8U dry-season and M3U10P drought regimes) in one-third of the years of the simulation (Table 4). The three flexible stocking-rate strategies yielded gross margins intermediate between the two fixed stocking-rate strategies.

Discussion

The present study is the first to report the impacts of climate variability on the GHGE from a simulated breeding–finishing beef property in northern Australia and has highlighted the considerable inter-annual variation that can occur in total GHGE and GHGE intensity due to seasonal conditions and management. In the 'fixed moderate' stocking-rate strategy, there was a 1.2 times difference in the total GHGE produced between the years with the lowest and highest emissions, but this increased up to a 2.7-fold difference in the 'flexible 20' strategy (Fig. 3*a*). The differences between years with the lowest and highest GHGE intensity were 1.2 and 3.9 times for the same two treatments (Fig. 3*b*). For flexible stocking-rate strategies, low GHGE intensity was predicted when herd size was decreasing with additional livestock sales due to poor seasonal conditions (e.g. 1995–1998) but high GHGE intensity was predicted when herd size was increasing from low numbers when more favourable seasonal conditions occurred (e.g. 1999–2003). These results from the dynamic modelling approach used in the study demonstrated the interactions among climate variability, stocking rate management strategies and GHGE (total and intensity). While a direct comparison with methods that estimate GHGE using 'steady-state' herd structures was not made in the present study, the results suggest that care must be taken when using static approaches to estimate GHGE, especially when flexible stocking strategies are used.

Of the strategies tested, the 'fixed moderate' stocking-rate strategy produced the lowest average GHGE intensity and least inter-annual variability (Fig. 3*b*), and maintained the highest rates of liveweight gain (Fig. 2*a*), highest branding percentage and lowest mortality rate (Table 2). These results were underpinned by the pasture condition in this strategy, which was predicted to have the highest percentage of perennial grasses and pasture growth, and the lowest runoff (Table 3). This conservative fixed stocking-rate strategy also yielded the highest average gross margin per AE carried and per hectare, and did not require any dry-season supplementary feeding (Table 4). Conversely, the 'fixed high' stocking-rate strategy had the least favourable outcome, generating the highest average GHGE intensity and the lowest average financial returns. The three flexible stocking-rate strategies were intermediate between the two fixed stocking policies, in terms of GHGE and profitability, although increasing inter-annual variation was observed with these strategies. The findings that lower GHGE intensity in northern beef production systems was closely related to higher liveweight gain and branding rates is consistent with previous research in the region (Bentley *et al*. 2008; Cullen *et al*. 2016).

The superior performance of the 'fixed moderate' stocking-rate strategy was consistent with results from the 'Wambiana' grazing trial, whereby the stocking-rate treatments that were around the assessed long-term carrying capacity of the site produced the highest liveweight gain per steer (O'Reagain *et al*. 2009). In the present simulation study, the 'fixed-high' stocking-rate strategy included more animals per unit area, but the stocking-rate target could not be maintained over the full course of the simulation. This finding is supported by other research, which has shown that higher stocking rates are unsustainable in areas where the climate is variable (Jones 1997). When stocking rates continue to be above the long-term carrying capacity, the condition of the land and its ability to be productive tend to deteriorate as the pasture community and soil are altered (MacLeod *et al*. 2004; Hunt *et al*. 2014). The low perennial grass percentage and pasture growth in the 'fixed high' strategy in the present study is evidence of this (Table 3).

Climate variability has a considerable impact on the profitability of farms (Ash *et al*. 2007; Browne *et al*. 2013) and flexible stocking strategies have been recommended for the northern Australian beef industry (Wilson and MacLeod 1991; Hunt 2008; McIvor 2012; Pahl *et al*. 2013). However, in all measures in the present study, none of the flexible stocking strategies performed better than the 'fixed moderate' strategy over the simulation period. Despite their intuitive appeal, a major challenge in pursuing flexible stocking-rate strategies is effecting the required adjustments in animal numbers at the appropriate time. For example, setting animal numbers on the basis of the end of season standing forage and not adjusting them before the end of the following growing season can lead to higher rates of utilisation than planned if the subsequent season produces poor pasture growth (McKeon *et al*. 2000; Pahl *et al*. 2013). From the perspective of sustaining pasture condition over time, the critical factor is likely to be conservatively utilising the actual growth of biomass during the growing season, which is less easy to accomplish operationally on extensive northern grazing systems (McKeon *et al*. 2004).

Overall, the GHGE intensity of beef production was lowest and least variable in the 'fixed moderate' stocking-rate strategy simulated. This finding supports a body of previous work (e.g. O'Reagain and Scanlan 2013) that recommends moderate stocking rates to enhance the profitability and ecological stability of beef production systems in northern Australia.

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