CSIRO PUBLISHING

Animal Production Science, 2021, **61**, 72–83
https://doi.org/10.1071/AN19691

Bio-economic evaluation of grazing-management options for beef cattle enterprises during drought episodes in semiarid grasslands of northern Australia

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Abstract

Context. The large inter-annual and decadal rainfall variability that occurs in northern Australian rangelands poses major challenges for the profitable and sustainable management of grazing businesses.

Aims. An integrated bio-economic modelling framework (GRASP integrated with Breedcow and Dynama (BCD)) was developed to assess the effect of alternative grazing-management options on the profitability and sustainability of a beef cattle enterprise in the central-western Mitchell grasslands of Queensland over a multi-decadal time period.

Methods. Four grazing-management strategies were simulated over a 36-year period (1982–2017) in the GRASP pasture-growth model, using historic climate records for Longreach in central-western Queensland. Simulated annual stocking rates and steer liveweight-gain predictions from GRASP were integrated with published functions for mortality and conception rates in beef-breeding cattle in northern Australia, and then used to develop dynamic BCD cattle-herd models and discounted cash-flow budgets over the last 30 years of the period (1988–2017), following a 6-year model-equilibration period. The grazing-management strategies differed in the extent to which stocking rates were adjusted each year, from a common starting point in Year 1, in response to changes in the amount of forage available at the end of the summer growing season (May). They ranged from a low flexibility of 'Safe stocking rate' (SSR) and 'Retain core herd' (RCH) strategies, to a moderate flexibility of 'Drought responsive' (DR), to a 'Fully flexible' (FF) strategy. The RCH strategy included the following two herd-management scenarios: (1) 'Retain herd structure', where a mix of cattle were sold in response to low pasture availability, and (2) 'Retain core breeders', where steers were sold before reducing the breeder herd. Herd-management scenarios within the DR and FF strategies examined five and four options respectively, to rebuild cattle numbers and utilise available pasture following herd reductions made in response to drought.

Key results. Property-level investment returns expressed as the internal rate of return (IRR) were poor for SSR (–0.09%) and the three other strategies when the herd was rebuilt following drought through natural increase alone (RCH, –0.27%; DR, –1.57%; and FF, –4.44%). However, positive IRR were achieved when the DR herd was rebuilt through purchasing a mix of cattle (1.70%), purchasing pregnant cows (1.45%), trading steers (0.50%) or accepting cattle on agistment (0.19%). A positive IRR of 0.70% was also achieved for the FF property when purchasing a mix of cattle to rebuild numbers. However, negative returns were obtained when either trading steers (–2.60%) or agistment (–0.11%) scenarios were applied to the FF property. Strategies that were either inflexible or highly flexible increased the risk of financial losses and business failure. Property-level pasture condition (expressed as the percentage of perennial grasses; %P) was initially 69%P and was maintained under the DR strategy (68%P; average of final 5 years). The SSR strategy increased pasture condition by 25% to 86%P, while the RCH and FF strategies decreased pasture condition by 29% (49%P) and 65% (24%P) respectively.

Conclusions. In a highly variable and unpredictable climate, managing stocking rates with a moderate degree of flexibility in response to pasture availability (DR) was the most profitable approach and also maintained pasture condition. However, it was essential to economic viability that the property was re-stocked as soon as possible, in line with pasture availability, once good seasonal conditions returned.

Implications. This bio-economic modelling analysis refines current grazing-management recommendations by providing insights into both the economic and sustainability consequences of stocking-rate flexibility in response to fluctuating pasture supply. Caution should be exercised in recommending either overly conservative safe stocking strategies that are inflexible, or overly flexible stocking strategies, due to the increased risk of very poor outcomes.

Additional keywords: beef cattle, bio-economic modelling, farm-management economics, perennial grasses, rangelands, rangeland management.

Received 6 December 2019, accepted 24 July 2020, published online 19 August 2020

Introduction

The beef cattle industry makes an important contribution to the Australian economy. In 2017–2018 it accounted for ~20% (AU$12 billion) of the total gross value of agricultural commodities produced (ABS 2019). In the extensive grazing lands of northern Australia used for beef cattle production, there is large inter-annual and decadal rainfall variability and associated major temporal variability in forage supply (Nicholls and Wong 1990; Love 2005; Cobon *et al*. 2019). This temporal variability in pasture production, and especially drought, with its abnormally prolonged dry periods, poses a major challenge for the sustainable and profitable management of grazing businesses (O'Reagain and Scanlan 2013). The best-practice grazing-management strategies promoted to managers of grazing businesses are intended to prevent serious pasture degradation (Scanlan and McIvor 2010; O'Reagain *et al*. 2011, 2014). However, northern Australian beef businesses are also challenged by pressures on long-term financial performance and viability due to an ongoing disconnect between asset values and returns, high debt levels and a declining trend in terms of trade (McCosker *et al*. 2010; McLean *et al*. 2014). To remain in production as a viable business, and to be resilient to drought, beef producers need to be profitable and to build capital over the longer term. To make profitable management decisions, beef producers need to appropriately assess the effect of various management strategies on profitability, the associated risks, and the period of time before benefits can be expected. The effects of alternative management strategies, including grazing-management options, are best assessed using property-level herd models that determine the marginal improvement in productivity and profitability (Malcolm 2000; Malcolm *et al*. 2005).

The GRASP pasture-growth model developed for northern Australia and rangeland pastures (McKeon *et al*. 2000; Rickert *et al*. 2000) has been integrated with the dynamic beef herd-model Enterprise (MacLeod and Ash 2001) and used to examine property-level economic implications of different grazing strategies for beef cattle businesses (e.g. Scanlan *et al*. 2013). However, Mayer (2013) and Mayer *et al*. (2012) proposed improved functions for prediction of conception and mortality rates of breeders under northern Australian conditions that can be applied in such herd and economic modelling.

In the present study, we have applied farm-management economics in a bio-economic modelling framework by integrating output from the GRASP pasture-growth model with the Breedcow and Dynama (BCD) cattle herd-budgeting software (Holmes *et al*. 2017), including applying the functions developed by Mayer *et al*. (2012). The objective was to assess the effect of alternative grazing-management options on the profitability and sustainability of a beef cattle enterprise in the central-western Mitchell grasslands of Queensland (Qld) as a region representative of the highly variable climate of northern Australia.

Materials and methods

Representative beef cattle enterprise

A hypothetical representative property situated near Longreach in the central-western Mitchell grasslands of Qld was developed on the basis of data from recent industry surveys and research relevant to the region (McIvor 2010; Bray *et al*. 2014; McGowan *et al*. 2014), as well as the expert opinion of scientists, beef extension officers and local beef producers. The property closely followed that described for the same region by Scanlan and McIvor (2010) and Scanlan *et al*. (2011). The representative property (16 200 ha) was primarily Mitchell grass (*Astrebla* spp.) and other native pastures growing on six land types comprising open downs (59%), wooded downs (21%), soft gidgee cleared (7%), soft gidgee wooded (3%), boree wooded downs (5%) and open alluvial plains (5%), (State of Queensland 2019). Pasture condition across all land types was assumed to start in land condition B (Scale A–D; Quirk and McIvor 2003), in accord with regional survey data (Beutel and Silcock 2008) with 69% perennial grasses (%P) in the pasture. The beef enterprise was considered as a self-replacing breeding and growing activity that relied on the production of weaners by a *Bos indicus* crossbred breeding herd. Each class of cattle in the herd was allocated to relevant land types and this was consistent for each alternative management strategy. The breeder component of the herd was allocated to the open downs land type, the heifers to wooded downs, boree wooded downs and open alluvial plains, and the steers to soft gidgee cleared and wooded, and wooded downs. The performance of each class of cattle was accumulated at the property level to indicate overall herd performance. A detailed description of the herd structures and dynamics, herd-performance parameters, cattle-management activities, treatments and cost assumptions required as inputs for the analysis are given by Bowen *et al*. (2019).

Grazing-management strategies applied in GRASP and in BCD

Four over-arching grazing-management strategies were investigated. In the first grazing-management strategy, 'Safe stocking rate' (SSR), the set stocking of ~1097 adult equivalents (AE) was determined by running the GRASP model (McKeon *et al*. 2000; Rickert *et al*. 2000) several times to establish the number of livestock that could be grazed so as to maintain the same average pasture condition, over the 36 years of simulation, as the initial pasture condition (69%P). The total number of cattle were held constant in the SSR strategy (0.1% change allowed from starting number in Year 1; Table 1). Rates for degradation and recovery of pasture condition determined for Mitchell grass pastures in the Barkly region of the Northern Territory were used in the model (Walsh and Cowley 2016), but otherwise the GRASP model parameters were primarily those of Scanlan and McIvor (2010). The target 'safe' utilisation rates of annual pasture biomass growth (kg dry matter (DM)/ha) and total standing DM (TSDM; kg DM/ha) at 1 May respectively, that were applied in the SSR analysis to achieve an average pasture condition of 69%P over 36 years were 22% and 30% for open downs, 20% and 25% for wooded downs, 30% and 35% for soft gidgee cleared, 18% and 20% for soft gidgee wooded, 22% and 30% for boree wooded downs, and 18% and 20% for open alluvial plains. The three subsequent grazing-management strategies started in the first year of simulation with the same initial

Table 1. The allowed changes, in both annual and absolute terms, in stocking rates of pastures over the 36-year GRASP simulation period (1982–2017) for four grazing-management strategies implemented for a beef enterprise in the central-western Mitchell grasslands of Queensland

GRASP, pasture growth model (McKeon *et al*. 2000; Rickert *et al*. 2000); SSR, Safe stocking rate; RCH, Retain core herd; DR, Drought responsive; FF, Fully flexible

Grazing-management strategy	Allowed change in stocking rate (%)			
	Annual increase	Annual decrease	Absolute increase	Absolute decrease
SSR	0.1	0.1	0.1	0.1
RCH	10	20	100	25
DR	30	60	100	75
FF	No limit	No limit	No limit	No limit

stocking rate as for the SSR strategy, but differed in de-stocking and re-stocking responsiveness to annual changes in TSDM of pasture on 1 May to target the utilisation rates identified previously (Table 1). The second strategy, 'Retain core herd' (RCH), had low flexibility in allowed changes to stocking rate, with the objective of retaining a core herd on the property during drought (retention of 75% of the initial, Year-1, AE regardless of drought). This was to reflect the perception of some property managers that this will allow a more rapid recovery in animal numbers and profitability once drought breaks. The third strategy, 'Drought responsive' (DR), had moderate flexibility in allowed changes to stocking rate but with the retention of 25% of initial AE, regardless of TSDM availability, to reflect a typical lower limit of livestock carried by producers during droughts (AgForce 2015). The fourth strategy, 'Fully flexible' (FF), had no limit applied to the degree to which stocking rates could be either decreased or increased on 1 May to target the specified utilisation of TSDM. The linear trend in the %P over the last 30 years of GRASP simulation, for the four grazing-management strategies on each of the six land types, were compared using grouped regression analysis, by using the statistical package GENSTAT for Windows (VSN International 2017). Distributional assumptions were assessed by visual inspection of residual and normal probability plots.

Herd-management scenarios applied in BCD

The economic value of alternative de-stocking, and subsequent re-stocking, options in response to drought were investigated through a series of herd-management scenarios applied within the BCD software (Holmes *et al*. 2017). Two herd-management scenarios within the RCH strategy were investigated, namely, (1) Retain herd structure, where a mix of cattle was sold in response to poor seasonal conditions, and (2) Retain core breeders, where steers were sold first, before reducing the breeder herd. The investigation of these two herd-management scenarios was undertaken to prevent the grazing-management and herd-reduction strategies being confounded in the analysis and to identify the economic value of retaining the core breeding herd in comparison to retaining a mix of cattle that maintained the same grazing pressure. In the RCH scenarios, cattle numbers were rebuilt following drought through natural increase only. Herd-management scenarios within the DR and FF strategies compared options to rebuild cattle numbers after significant herd reductions in response to drought, and comprised (1) Natural increase, (2) Purchasing pregnant (i.e. pregnancy-tested in-calf) cows, (3) Repurchasing components of the herd that had been sold (i.e. 'Purchase replacement herd'), (4) Trading steers, and (5) Agistment income. The Purchase pregnant cows scenario (2) was not examined for the FF strategy due to little difference between (2) and (3) in the preceding DR analysis. Herd reduction for DR and FF scenarios was through additional female sales (rather than bringing steer sales forward) due to little difference between Scenarios (1) and (2) in the RCH analysis. The approach to de-stocking and re-stocking for all 12 grazing-management options (grazing-management strategy and herd-management scenario combination) is summarised in Table 2.

Supplementation rules

In each year, supplementation rules were applied in all modelled options in response to GRASP output. Three stages of feeding were applied depending on the severity of nutritional deficits for cattle predicted by the models. Feeding levels and expected biological benefits were determined with reference to Winks (1984) and Dixon (1998) and the opinion of research and beef extension staff with extensive knowledge of supplementation responses across northern Australia, particularly that of M. Sullivan and R. Dixon. Stage 1 supplementation, namely, supplementary non-protein nitrogen (NPN), was triggered in years when the GRASP-predicted annual steer liveweight gain (LWG) was 50–100 kg/head (cf. 148 kg/head expected, on average; Bowen *et al*. 2019). A loose mineral-mix supplement (30% urea, 8% ammonium sulfate, 62% salt; AU$636/t on-property) was fed to breeders (156 g/head.day), yearling heifers (94 g/head.day) and weaners (78 g/head.day) for 120 days (~4 months). The assumed benefit to the breeder from Stage 1 supplementation was 6 kg liveweight/month for each of the 4 months of feeding. Stage 2 supplementation, namely, supplementary NPN and whole cottonseed, was triggered in years when the estimated steer LWG was 0–50 kg/head. Initially, breeders, yearling and weaner heifers were fed NPN loose mineral mix for 90 days, as described for Stage 1. This was followed by whole cottonseed in combination with NPN loose mineral mix for 120 days where whole cottonseed (AU$550/t on-property) was fed at 1300, 800 and 600 g/head.day for breeders, yearling heifers and weaners respectively, and NPN loose mineral mix was fed at half the rates for Stage 1. In addition, yearling steers were fed NPN loose mineral mix at 94 g/head.day for 210 days. The assumed benefit to the breeder from feeding supplement was 6 kg liveweight/month for each of the 3 months of NPN loose mineral-mix feeding and then 8 kg liveweight/month for each of the 4 months of whole-cottonseed feeding, i.e. 50 kg liveweight total benefit. Stage 3 supplementation, that is, drought feeding hay, was triggered in every month for which GRASP predicted TSDM

Table 2. The modelling approach applied in Breedcow and Dynama (BCD) herd-modelling software (Holmes *et al*. 2017) to assess the economic value of alternative de-stocking, and subsequent re-stocking, options in response to drought for a beef enterprise in the central-western Mitchell grasslands of Queensland

AE, adult equivalent; GRASP, pasture growth model (McKeon *et al*. 2000; Rickert *et al*. 2000); PTIC, pregnancy-tested in-calf; SSR, Safe stocking rate; RCH, Retain core herd; DR, Drought responsive; FF, Fully flexible

Grazing-management option	Approach to de-stocking in response to drought	Approach to re-stocking following drought
SSR	Natural decrease only (herd-productivity and -mortality responses); no additional sales	Natural increase only (retention of breeders and heifers, minimal culling); no additional purchases
RCH		
Retain herd structure	Mix of cattle sold; steers sold at normal target age	Natural increase only; no additional purchases
Retain core breeders	Steers sold first before reducing the breeder herd	Natural increase only; no additional purchases
DR		
Natural increase	Mix of cattle sold; steers sold at normal target age	Natural increase only; no additional purchases
Purchase pregnant cows	Mix of cattle sold; steers sold at normal target age	Annual purchase of sufficient PTIC cows to match the AE capacity estimated by GRASP
Purchase replacement herd	Mix of cattle sold; steers sold at normal target age	Annual purchase of steers, heifers and PTIC cows to target optimal herd structure and to match the AE capacity estimated by GRASP
Trading steers	Mix of cattle sold; steers sold at normal target age	Annual purchase of 18-month-old steers in June to match the AE capacity estimated by GRASP, and sale 12 months later
Agistment income	Mix of cattle sold; steers sold at normal target age	Cattle taken on agistment to match spare AE capacity estimated by GRASP with numbers reduced over time as the base herd rebuilds
FF		
Natural increase	Mix of cattle sold; steers sold at normal target age	Natural increase only; no additional purchases
Purchase replacement herd	Mix of cattle sold; steers sold at normal target age	Annual purchase of steers, heifers and PTIC cows to target optimal herd structure and to match the AE capacity estimated by GRASP
Trading steers	Mix of cattle sold; steers sold at normal target age	Annual purchase of 18-month old steers in June to match the AE capacity estimated by GRASP, and sale 12 months later
Agistment income	Mix of cattle sold; steers sold at normal target age	Cattle taken on agistment to match spare AE capacity estimated by GRASP with numbers reduced over time as the base herd rebuilds

of pasture was <300 kg DM/ha. This biomass-availability threshold was derived from long-term grazing-trial data from Mitchell grasslands near Julia Creek, Qld (Orr and Phelps 2013) and Phelps (2006). All cattle except yearling steers were fed hay at 1.6% of liveweight (AU$400/t on-property). The assumed benefit from feeding hay was a halving of livestock mortality rates otherwise predicted for that year.

Approach to integrated bio-economic evaluation

The implications of the four grazing-management strategies, and their herd-management scenarios, on the productivity and profitability of the beef cattle enterprise were investigated. For each land type, simulated annual stocking rates and steer LWG predictions from the GRASP pasture-growth model over a climate sequence of 36 years (1982–2017) were integrated with published functions for mortality and conception rates in beef breeding cattle in northern Australia (Mayer *et al*. 2012), so as to develop dynamic BCD cattle herd models. These were used as inputs for discounted cash-flow budgets over the last 30 years of the period (1988–2017) after allowing for a 6-year model-equilibration period.

Parameterisation of GRASP included adjustment of predicted steer annual LWG for all land types to provide reasonable agreement with expected average LWG from regional research and survey data (e.g. McGowan *et al*. 2014). The limitation of no available data to support a relationship between change in steer LWG (from GRASP) and change in breeder reproduction efficiency in northern Australia was overcome by using the change in steer LWG modelled in GRASP as an index to vary the median reproduction performance of breeding herds located on the northern Mitchell grass-downs region, as identified by research on commercial cattle properties (McGowan *et al*. 2014). In this way, grazing-management strategies producing higher (or lower) steer annual LWG in GRASP had those advantages or disadvantages reflected as a relative shift in the median reproductive performance identified by relevant research and survey data in the region. The size of the relative shift was related to the level of change in reproductive performance indicated by the combination of Mayer *et al*. (2012) functions and GRASP steer annual LWG data. The Mayer *et al*. (2012) equations were directly applied to model the effect of change in breeder liveweight on breeder mortality, and also heifer conception rates in accordance with data of Schatz (2010).

Annual steer LWG predicted by GRASP were accumulated from each calving date to represent the growth path of steers and heifers. Heifer growth rates were adjusted to be 5% lower on an annual basis when steer growth rates were both positive and negative, as indicated by the data of Fordyce *et al*. (1993). Calf growth rates pre-weaning were adjusted to reflect the potential impact of the range of steer growth rates estimated by GRASP on the average weight of weaners. The growth of steers and heifers in up to 5 years immediately before the 30-year period of economic analysis were accounted for in the weights of steers and heifers sold or mated in the initial years.

Cull-cow sale weights were calculated by adding (or subtracting) the GRASP annual steer LWG to a predefined cull-cow reference weight (450 kg) to achieve a median of 450 kg in the paddock in the SSR herd model. Scenarios that achieved higher or lower annual steer LWG than did the SSR strategy achieved higher or lower cull-cow weights and a different median sale weight. In the model, cows were culled and sold in June, generally just after weaning a calf. This practice was expected to affect cull-cow sale weights at the point of sale, but the combination of GRASP annual steer weight gains or losses, plus the adjustment of cull-cow sale weight around the expected median, allowed the differences between the management practices and seasonal conditions being modelled to be reflected in cull-cow income.

To identify the most profitable herd structure and age of cattle turn-off for the representative property, as well as the number of cattle, on average, in each age group and class, steady-state herd modelling in BCD was conducted on the basis of the expected median herd data for the representative property. Subsequently, the total return on investment at the property level was identified for each of the 12 grazing-management options for the 30-year investment period. Finally, the Retain herd structure scenario was applied as a base for comparison with all other scenarios within the three grazing-management strategies of RCH, DR and FF. A marginal analysis was applied in the form of partial discounted cash flow (DCF) budgets to provide an estimate of the return on extra capital invested in changing from the RCH Retain herd structure to the alternative management options, also over 30 years. The SSR strategy was not considered in the marginal analysis as it was not seen as being representative of pasture-management strategies commonly applied in the region. The SSR strategy was applied only to determine a sufficiently conservative stocking rate that would maintain the same average pasture condition as the initial pasture condition over the long term, namely, over the 36 years of simulation.

Discounted cash-flow techniques were applied at a 5% discount rate to calculate either (1) the property-level or (2) the marginal returns associated with (1) all the capital and resources invested or (2) the additional capital and resources invested respectively. The DCF analysis was compiled in real (constant value) terms and it was assumed that inflation would affect all costs and benefits equally. Costs were expressed in the price level of the present year (2018), while recent livestock selling prices were averaged and then applied to represent the real prices that are likely to be experienced in the future. The BCD herd-budgeting software applied investment-analysis methods as described by Robinson and Barry (1996), Campbell and Brown (2003) and Malcolm *et al*. (2005). The models contained livestock schedules linked to DCF budgets for each alternative grazing-management option. The long 30-year analysis interval was selected as an appropriate period over which to study effects of inter-annual and decadal rainfall variability in the region.

Economic and financial criterion used to evaluate the grazing-management options

The economic criteria calculated were the net present value (NPV) at the required real rate of return (5%; as the real opportunity cost of funds to the producer) and the internal rate of return (IRR). The returns to each grazing-management option were calculated as either returns to the discrete whole-farm investment or as marginal returns that looked at the difference between a grazing-management option and an alternative grazing-management option. The NPV for the discrete whole-farm investment was calculated over the 30-year life of the investment, expressed in present day terms at the level of operating profit. The latter was calculated as

$$\begin{aligned}\text{Operating profit} &= (\text{total receipts} - \text{variable costs} \\ &= \text{total gross margin}) - \text{overheads}\end{aligned}.$$

Hence, the operating profit was defined as the return to total capital invested after the variable and overhead (fixed) costs involved in earning the revenue were deducted. Operating profit represented the reward to all of the capital managed by the business and was calculated net of an allowance for the labour and management of the owner. Opening and salvage values for land, plant and livestock were applied at the beginning and end of the DCF analysis to capture the opening and residual value of assets. Plant replacement was incurred as a capital cost less a salvage value in the year it was expected to be incurred during the investment period. In the marginal analysis, which assessed the value of implementing a change from the base situation of RCH Retain herd structure, an annualised, amortised NPV was calculated at the discount rate over the investment period. This was undertaken to assist in communicating the marginal difference between the base property and the property after the management option was implemented. This annualised NPV measure is not the same as the annual difference in operating profit between the two options, but it is presented to identify the approximate annual average improvement in profit generated by the implementation of the alternative grazing-management options. The IRR was calculated as the discount rate at which the present value of income equalled the present value of total expenditure (capital and annual costs), that is, the break-even discount rate. The financial criteria calculated were peak deficit and the number of years to the peak deficit. The beef enterprise started with no debt, but debt was accumulated and interest paid as required for the implementation of the grazing-management option. Peak deficit in cash flow was calculated assuming interest was paid on the deficit and compounded for each additional year in the investment period.

Results

Modelled pasture, cattle and herd outputs

The average (410 mm) and median (426 mm) annual rainfall, and the year-to-year variability in rainfall (CV 41%), for the 36-year GRASP pasture simulation period (1982–2017) were similar to the standard 30-year climate normal period for Longreach (1961–1990; 424 mm, 437 mm, CV 36%). The rainfall distribution over the period 1982–2017 (Fig. 1*a*) shows that over the 30-year herd modelling period (1988–2017), there were four 'drought' episodes of very low rainfall, and of potential de-stocking and later re-stocking, dependent on the modelling assumptions for each grazing-management strategy. Regardless of the grazing-management strategy, the 12-month pasture-biomass growth modelled in GRASP over 36 years (e.g. open downs; Fig. 1*b*) closely followed the annual rainfall pattern, which varied widely from well below average to well above average for the region. Even though pasture results are presented for all land types, for succinctness, graphical

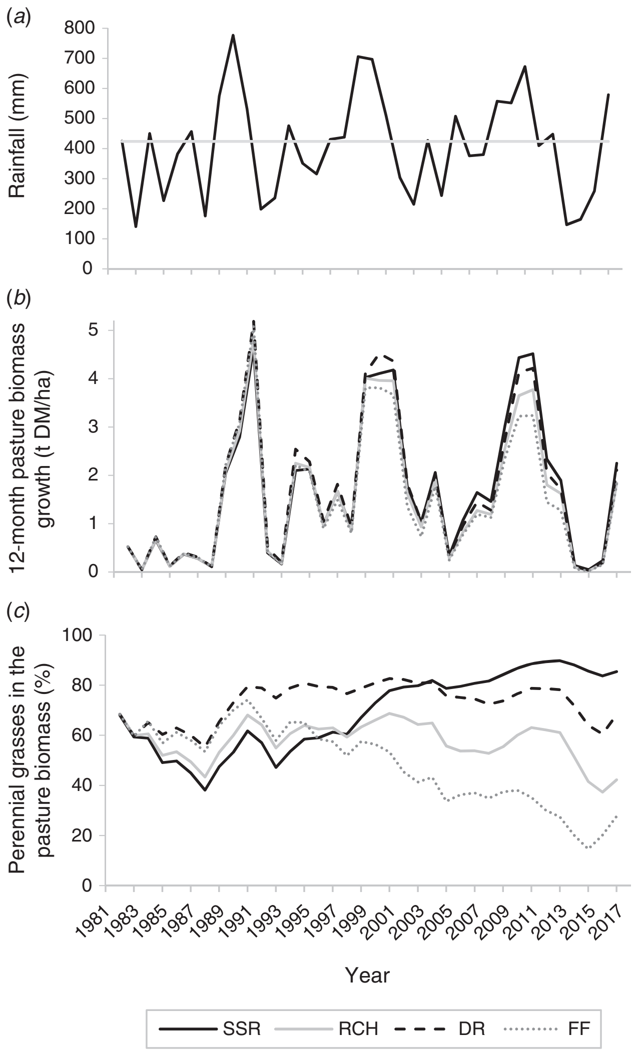

Fig. 1. (*a*) Annual rainfall, and (*b*) annual pasture-biomass growth and (*c*) proportion of the pasture biomass as perennial grasses over 36 years of GRASP pasture-growth simulation (1982–2017; McKeon *et al*. 2000; Rickert *et al*. 2000) for the open downs land type (59% of total property area) in the central-western Mitchell grasslands of Queensland under four alternative grazing-management strategies (SSR, Safe stocking rate; RCH, Retain core herd; DR, Drought responsive; FF, Fully flexible). Pasture biomass growth is on the basis that GRASP-predicted grazing pressure is matched in the Breedcow and Dynama (BCD) herd model (Holmes *et al*. 2017). The figure showing annual rainfall also indicates the average rainfall over the climate normal period (1961–1990; 424 mm).

presentation is limited to the primary land type of open downs, which represented 59% of the property. The %P, as modelled in GRASP, fluctuated over the period, but there was a divergence over time for the four grazing-management strategies (Fig. 1*c*). The linear trend in %P over the 30 years of regression analysis (1988–2017) was positive ($P < 0.001$) for the SSR strategy and negative ($P < 0.001$) for the FF strategy, for all land types (Table 3). The RCH strategy resulted in a significant negative trend in %P for all land types except soft gidgee (cleared and wooded; 10% of area), which showed a significant positive trend. The DR strategy caused no trend in %P for 88% of the property area encompassing open downs (Fig. 1*c*), wooded downs, soft gidgee wooded and boree wooded downs. A positive trend due to the DR strategy was observed for soft gidgee cleared (7% of area) and a negative trend was observed for open alluvia (5% of area). Property-level pasture condition (expressed as %P) was initially 69%P and was maintained under the DR strategy (68%P; average of the final 5 years; Table 3). The SSR strategy increased pasture condition by 25%, to 86%P, while the RCH and FF strategies decreased pasture condition by 29% (49%P) and 65% (24%P) respectively.

Property-level annual pasture-biomass growth and steer LWG, averaged over 36 years, were greatest for the DR strategy and least for the FF strategy (1599 kg DM/ha and 127 kg/head cf. 1370 kg DM/ha and 98 kg/head respectively). The SSR strategy resulted in greater annual pasture-biomass growth and steer LWG than did the RCH strategy (1575 kg DM/ha and 119 kg/head cf. 1466 kg DM/ha and 108 kg/head respectively). The average number of AE modelled in GRASP to run on the property was least for the SSR strategy (1097), intermediate for the RCH (1598) and the DR (1609) strategies and greatest for the FF strategy (2274). When the GRASP output for the grazing-management options was integrated with cattle herd models, the average number of AE over 30 years was similar to the target GRASP AE when scenarios to rebuild cattle numbers after drought were applied (Table 4). Rebuilding numbers through natural increase alone did not allow GRASP target AE to be achieved. The greatest average annual mortalities (30), resulted from the FF strategy with the Purchase replacement herd and Trading steers scenarios. The greatest average annual number of weaners was produced by the FF strategy with the Purchase replacement herd scenario (663), while the greatest average annual livestock sales resulted from the FF strategy with Trading steers scenario (2198). Stages 1 and 2 supplementary feeding were triggered in no more than 3 years over the 30-year period for all grazing-management strategies (Table 5). The greatest instance of drought feeding of hay (Stage 3 supplementary feeding) occurred for the FF strategy (6 years of 30; Table 5).

Modelled economic and financial indicators

Property-level investment returns were poor for the inflexible grazing-management strategies, that is, SSR and RCH (IRR –0.09% and –0.27% respectively; Table 6). Returns were even poorer for DR and FF grazing-management strategies when cattle herd numbers were rebuilt through natural increase

Table 3. Property-level, average percentage of perennial grasses in the pasture biomass (%P) over the final 5 years, and slope and significance of the linear trend in %P over the final 30 years, of the 36-year GRASP modelling period (1982–2017), due to implementing one of four grazing-management strategies on six land types in the central-western Mitchell grasslands of Queensland

AdjR^2, adjusted R^2; GRASP, pasture growth model (McKeon *et al*. 2000; Rickert *et al*. 2000); SSR, Safe stocking rate; RCH, Retain core herd; DR, Drought responsive; FF, Fully flexible. The area of each land type is expressed as a percentage of the total property area. The property-level, Year 1 value for %P was 69%

Grazing-management strategy	Linear trend in %P over 30 years: Open downs (59%)	Wooded downs (21%)	Soft gidgee, cleared (7%)	Soft gidgee, wooded (3%)	Boree wooded downs (5%)	Open alluvial plains (5%)	Property-level, average %P (final 5 years)
SSR	1.6, $P < 0.001$	1.5, $P < 0.001$	1.5, $P < 0.001$	1.2, $P < 0.001$	1.4, $P < 0.001$	1.5, $P < 0.001$	86
RCH	–0.36, $P = 0.009$	–0.51, $P < 0.001$	0.48, $P < 0.001$	0.31, $P = 0.005$	–0.30, $P = 0.022$	–0.65, $P < 0.001$	49
DR	–0.09, $P = 0.530$	–0.22, $P = 0.113$	0.39, $P = 0.004$	0.19, $P = 0.089$	–0.05, $P = 0.682$	–0.45, $P < 0.001$	68
FF	–1.7, $P < 0.001$	–1.6, $P < 0.001$	–0.9, $P < 0.001$	–1.8, $P < 0.001$	–1.9, $P < 0.001$	–1.6, $P < 0.001$	24
AdjR^2	85	84	74	93	88	87	–

Table 4. Annual cattle-herd statistics of adult equivalents (AE) or livestock numbers of mortalities, weaners and livestock sold over 30 years (1988–2017) for 12 grazing-management options implemented for a beef enterprise in the central-western Mitchell grasslands of Queensland

SSR, Safe stocking rate; RCH, Retain core herd; DR, Drought responsive; FF, Fully flexible

Grazing-management option	AE carried			Mortalities			Weaners			Livestock sold		
	Median	Average	Range	Median	Average	Range	Median	Average	Range	Median	Average	Range
SSR	1095	1037	532–1266	1	10	0–186	408	382	117–478	399	371	162–458
RCH												
Retain herd structure	1567	1469	573–2238	6	22	0–340	559	521	46–933	484	528	168–1240
Retain core breeders	1614	1527	601–2235	5	22	0–344	645	572	46–885	480	579	188–1541
DR												
Natural increase	590	690	209–1563	0	3	0–69	232	250	36–576	202	281	44–1516
Purchase pregnant cows	1819	1571		5	7	0–85	644	558	36–874	620	639	106–1844
Purchase replacement herd	1912	1650	327–2515	5	7	0–86	656	570	36–898	757	699	149–1845
Trading steers	1533	1623	209–3467	11	13	0–90	232	250	36–576	1252	1272	44–3650
Agistment income	1688	1801	297–3467	0	3	0–69	232	250	36–576	202	281	44–1516
FF												
Natural increase	451	512	176–1074	0	9	0–208	158	176	25–428	165	198	43–1008
Purchase replacement herd	2263	2355	44–5956	8	30	0–531	648	663	3–2106	1054	1519	41–7040
Trading steers	2068	2361	323–6416	20	30	1–208	158	176	25–428	1888	2198	257–6931
Agistment income	2068	2361	323–6416	0	9	0–208	158	176	25–428	165	198	43–1008

Table 5. Frequency of supplement and drought feeding over the 30-year Breedcow and Dynama (BCD; Holmes *et al*. 2017) herd- and economic-modelling period (1988–2017) for four grazing-management strategies implemented for a beef enterprise in the central-western Mitchell grasslands of Queensland

LWG, liveweight gain; NPN, non-protein nitrogen; TSDM, total standing dry matter of pasture; SSR, Safe stocking rate; RCH, Retain core herd; DR, Drought responsive; FF, Fully flexible

Grazing-management strategy	Supplement and drought feeding frequency (years): Stage 1: NPN; annual steer LWG 50–100 kg/head	Stage 2: NPN + whole cottonseed; annual steer LWG 0–50 kg/head	Stage 3: drought feeding hay; TSDM <300 kg DM/ha
SSR	3	1	2
RCH	3	0	4
DR	1	2	4
FF	3	3	6

Table 6. Property-level investment returns expressed as the net present value (NPV) and internal rate of return (IRR) over 30 years for 12 grazing-management options implemented for a beef enterprise in the central-western Mitchell grasslands of Queensland

SSR, Safe stocking rate; RCH, Retain core herd; DR, Drought responsive; FF, Fully flexible. NPV, the net present value of an investment, referring to the net returns (income minus costs) over the 30-year life of the investment. IRR, the internal rate of return, i.e. the rate of return on the capital invested. It is the discount rate at which the present value of income from the project equals the present value of total expenditure (capital and annual costs) on the project, i.e. the break-even discount rate. The IRR represents the return to the investment in the land, plant and livestock over the 30-year period. Closing asset values were not adjusted for any potential (or hoped for) real increase in value

Grazing-management option	NPV	IRR (%)
SSR	–AU$4 832 019	–0.09
RCH		
Retain herd structure	– AU$4 688 873	–0.28
Retain core breeders	–AU$4 682 528	–0.26
DR		
Natural increase	–AU$5 478 918	–1.57
Purchase pregnant cows	–AU$3 356 739	1.45
Purchase replacement herd	–AU$3 147 928	1.70
Trading steers	–AU$4 230 962	0.50
Agistment income	–AU$4 058 105	0.19
FF		
Natural increase	–AU$6 391 257	–4.44
Purchase replacement herd	–AU$4 694 744	0.70
Trading steers	–AU$7 002 808	–2.60
Agistment income	–AU$3 430 553	–0.11

alone (IRR –1.57% and –4.44% respectively). The marginal returns for changing from a Retain herd structure to a Retain core breeders scenario (~AU$5000 extra profit over 30 years; Table 7) indicated that, over the modelled sequence of years, there was no real difference in economic performance between selling breeders or selling steers first when reducing numbers in response to drought. Positive property-level investment returns were achieved under the DR strategy when cattle numbers were rebuilt after drought through either purchasing a mix of cattle or purchasing pregnant cows (IRR 1.70% and 1.45% respectively; Table 6), while the returns from trading steers and agistment income scenarios were considered low (IRR 0.50% and 0.19% respectively). The only FF scenario to produce positive returns was where a mix of cattle were purchased to rebuild the herd (IRR 0.70%; Table 6). Moving from an RCH Retain herd structure scenario to an alternative grazing-management option improved profitability for all, except where natural increase in cattle numbers was allowed to occur after herd reductions (DR and FF strategies) and with trading steers in the FF strategy (Table 7). Property-level NPV was negative for the property, with all grazing-management options, reflecting the property returns being less than the opportunity cost of funds of 5% (Table 6).

Discussion

The present study represents the first known attempt to incorporate published functions for prediction of conception and mortality rates of beef cattle breeders under northern

Table 7. The value over 30 years of implementing grazing-management options to improve profitability and drought resilience of a representative beef enterprise in the central-western Mitchell grasslands of Queensland compared with the base situation of Retain core herd (RCH), Retain herd structure

DR, Drought responsive; FF, Fully flexible; n.a., not available or not possible to calculate. NPV is the net present value of an investment, referring to the net returns (income minus costs) over the 30-year life of the investment and represents the extra return added by the management option, i.e. it is the difference between the base grazing-management option of RCH Retain herd structure, and the same property after the alternative grazing-management option is implemented. The annualised NPV represents the average annual change in NPV over 30 years, resulting from implementation of the alternative grazing-management option and can be considered as an approximation of the change in profit per year. Peak deficit is the maximum difference in cash flow between the alternative grazing-management option and the base situation of RCH retain herd structure, over the 30-year period of the analysis. It is a measure of riskiness

Grazing-management option	NPV of change	Annualised NPV	Peak deficit (with interest)	Years to peak deficit
RCH				
Retain core breeders	AU$5000	AU$300	–AU$144 100	4
DR				
Natural increase	–AU$642 700	–AU$41800	–AU$3 206 100	27
Purchase pregnant cows	AU$1 457 400	AU$94 800	n.a.	n.a.
Purchase replacement herd	AU$1 666 200	AU$108 400	n.a.	n.a.
Trading steers	AU$605 200	AU$39 400	–AU$133 300	22
Agistment income	AU$778 100	AU$50 600	n.a.	n.a.
FF				
Natural increase	–AU$1 037 400	–AU$67 500	–AU$4 018 700	27
Purchase replacement herd	AU$230 800	AU$15 000	–AU$3 817 500	13
Trading steers	–AU$2 184 900	–AU$142 100	–AU$7 504 400	23
Agistment income	AU$1 387 400	AU$90 300	AU$0	n.a.

Australian conditions (Mayer *et al*. 2012) into an integrated bio-economic modelling framework that can be used to assess the property-level effects of both the economic and sustainability consequences of alternative grazing-management options. Additional advantages of our approach over previous modelling efforts include (1) the identification of an optimum herd structure for the property before integrating GRASP pasture data, (2) the use of published research data from McGowan *et al*. (2014), for cattle mortality and reproductive performance in the target region, to moderate the functions applied to GRASP output and (3) the use of predicted steer LWG over each annual period to determine AE rating and, hence, grazing pressure applied.

Our analysis demonstrated that, in a highly variable climate, grazing-management strategies with a moderate degree of flexibility in changing livestock numbers from season-to-season in response to pasture availability are likely to be the most profitable. For instance, the DR strategy where annual increases and decreases in livestock numbers were limited to 30% and 60% respectively, and cattle numbers were rebuilt following drought through purchasing either a mix of cattle or pregnant cows, produced the greatest property-level investment returns over 30 years of 1.70% and 1.45% IRR respectively. Furthermore, over 36 years of GRASP pasture-growth simulation, this grazing-management strategy maintained the %P in the pasture at the property level (68%P average over the final 5 years cf. 69%P in Year 1).

Inflexible grazing-management strategies based on set-stocking at low numbers to maintain long-term pasture condition (SSR strategy) or small annual changes of 10% increase and 20% decrease in livestock numbers (RCH) resulted in negative property-level returns over 30 years of –0.09% and –0.27% IRR respectively. While the SSR strategy resulted in a highly significant positive trend in %P in the pasture for all land types over 30 years, the RCH strategy resulted in a significant negative trend over 90% of the property area and a positive trend for only 10% of the property area.

The highly significant positive trend in pasture condition over 30 years for the SSR strategy, over a climate sequence that included four significant drought events, reflects (1) the conservative stocking rates, and (2) the resulting low pasture-utilisation rates achieved, to ensure that the average %P over 36 years was the same as in Year 1 (i.e. 69%). This approach in setting long-term livestock numbers is taken to prevent pasture- and land-condition decline over unknown future climate sequences. However, there is evidence that land managers are applying a higher stocking pressure in the Mitchell grasslands bioregion than that recommended using such conservative approaches, and that this is increasing over time (Commonwealth of Australia 2008; Bray *et al*. 2014). Further, there is evidence to indicate that high levels of grazing pressure may be contributing to declining land condition over time (Beutel and Silcock 2008). Data from other rangeland regions in Qld suggest that financial pressures are likely to be contributors to high stocking rates (Rolfe *et al*. 2016; Bowen and Chudleigh 2017, 2018). Further, research has indicated a clear economic advantage over the short to long term (i.e. up to 30 years) from increasing pasture-utilisation rates, even with declining land condition and animal performance (Teague *et al*. 2009; Burrows *et al*. 2010; Star *et al*. 2013; Bowen and Chudleigh 2018). This has demonstrated the tension between achieving profitable grazing businesses and maintaining land condition over time. In our study, the most profitable scenarios under the DR strategy carried average AE on the property similar to those of the unprofitable scenarios in the RCH strategy, but avoided decline in %P due to greater flexibility in reducing stock numbers in response to declining pasture availability in drought.

In the present study, the more extreme grazing-management strategy of FF, with no limits to annual changes in stocking rate to match pasture available on 1 May, resulted in negative property-level returns for all herd-management scenarios except where a mix of cattle was purchased to rebuild the herd following drought (0.70% IRR). The poor returns for this grazing-management strategy were related to the increased riskiness of trading such large numbers of livestock in a variable production environment, particularly with the modelling limitation of one allowed change in the stocking rate per year. This limitation had substantial negative effects on profitability and pasture condition in years when rainfall over the pasture growing season was insufficient to support the cattle numbers set previously on 1 May, resulting in poor LWG performance, high mortalities, large supplement and hay-feeding costs, and high levels of utilisation of annual pasture-biomass growth. The limitation of a single annual adjustment in stocking rates was also recognised by Hunt (2008) and Pahl *et al*. (2016) who concluded that more than one adjustment per annum in stocking rate would greatly improve the sustainability and long-term cattle productivity of more flexible grazing-management strategies. However, even with improved profitability and sustainability outcomes, the FF strategy is unlikely to be adopted by beef property managers. The unlikely adoption is related to increased riskiness due to the large capital flows, increased transaction costs and price risk associated with purchasing such large numbers of livestock for potentially short periods of time.

Our study clearly indicated that it was essential to economic viability of the beef business that re-stocking occurs as soon as possible following drought, to match pasture availability, once good seasonal conditions return. All herd-management scenarios where the herd was rebuilt following drought-related de-stocking through only natural increase in livestock numbers resulted in negative property-level returns (RCH, –0.27%, DR, –1.57%, and FF, –4.44% IRR). However, positive IRR were achieved when the DR herd was rebuilt through either purchasing a mix of cattle (1.70%), purchasing pregnant cows (1.45%), trading steers (0.50%) or taking cattle on agistment (0.19%). A positive IRR of 0.70% was also achieved for the FF strategy when purchasing a mix of cattle to rebuild numbers. Taking stock on agistment during the drought-recovery phase substantially reduced the risk associated with that phase, due to more positive cumulative cash flows early in the climate sequence, but was a less profitable scenario for the DR strategy than was purchasing livestock to rebuild the breeding herd or trading cattle. However, the authors strongly recommend that the relative profitability of alternative re-stocking options following drought for individual property managers should be assessed each time the decision is being made. This should be undertaken by looking first at the immediate impact on cash flow and profit of the available choices and then, second, considering the medium-term impact on herd structure, profit and cash flow, by using herd-budgeting software such as BCD (Holmes *et al*. 2017).

Manipulating the component of the herd sold down first in response to drought did not change the returns achieved by the RCH strategy, with the marginal returns from changing from a Retain herd structure to a Retain core breeders scenario (~AU$5000 extra profit over 30 years), indicating no real economic difference between the scenarios. This result was largely due to the necessity, for both scenarios, to eventually sell numbers from all classes of cattle to achieve the level of de-stocking required in the more serious drought periods. Regardless, the decision about which class of cattle to sell first should be determined by the current market prices, and those expected at the start of the recovery phase, for each class of cattle at the time the decision is being made to de-stock. Additionally, these price expectations should be combined with the expected productivity of each class during the drought to estimate the impact on future profit.

A key influence that usually underpins grazing managers' decision-making in highly variable production environments, such as the central-western Mitchell grasslands of Qld, is risk (Anderson *et al*. 1977; Binswanger 1980). All grazing-management strategies available in the region, including those modelled in the present study, have high levels of risk largely due to the major temporal variability in forage supply. Inflexible stocking strategies, such as the SSR and RCH strategies, have a heightened risk of business failure due to the reliance on purchased hay during extended drought periods and an inability to take advantage of the better years. The moderately flexible DR strategy, which resulted in substantial reductions in livestock numbers during drought periods, was more profitable than less flexible strategies only when the risky approach of purchasing large numbers of livestock was incorporated to more rapidly rebuild stock numbers when better seasons occurred. This was critical to the greater profitability of the DR strategy over 30 years. Even so, the financial risks associated with the expected borrowings required to rebuild stock numbers rapidly during the drought-recovery phase may lead to some managers preferring to take stock on agistment, while rebuilding herd numbers. Nonetheless, utilising agistment income is expected to result in lower profitability than would rebuilding herd numbers through livestock purchases. As already discussed, the more extreme FF strategy resulted in even greater riskiness in this variable production environment than did the moderately flexible DR strategy.

Our analysis indicated that capital constraints and perceived risk are likely to play a large role in the level and the rate at which a management strategy is likely to be adopted and implemented. Applying a method that appropriately highlights the financial risks associated with the implementation of a management strategy, as well as the potential economic benefits, is necessary to assist understanding of the nature of the alternative strategies. This assertion was also made by Foran *et al*. (1990) who concluded that the 'whole-of-property' approach is essential for both comparing management options and for setting priorities for research and development in the northern beef industry.

In the present study, the use of GRASP and BCD software in an integrated modelling approach allowed simulation of the effects of grazing- and herd-management options in a highly variable climate. Although every effort has been made to ensure that the results generated are broadly indicative of what might happen on Mitchell grasslands in central-western Qld, the results must be interpreted in the context of the modelling limitations. These include (1) the relatively simple grazing rules applied in GRASP, particularly the inability to alter livestock numbers more than once per year, (2) the lack of feedback to GRASP for changes in grazing pressure and pasture condition, or individual animal LWG, resulting from changes in herd dynamics (e.g. mortality and reproductive rates, sale strategies, changing herd structure) or supplement feeding, (3) the restriction of the evaluations to only one historical climate sequence of 36 years, (4) the reliance of steer LWG predictions on user-defined parameters and (5) a paucity of scientific data to inform rates of pasture decline and improvement for individual pasture communities and regions in GRASP. Furthermore, as the biological and economic outputs relate to the modelled property and may vary with a different set of assumptions, responses obtained here should be considered only as guidelines. Assessment of alternative grazing-management options should ideally be undertaken on an individual-property basis and with consideration of current management goals, to identify the most appropriate changes for each business.

In conclusion, in a highly variable and unpredictable climate, managing stocking rates with a moderate degree of flexibility in response to pasture availability was the most profitable approach and also maintained pasture condition. However, it was essential to economic viability that re-stocking occurred as soon as possible, in line with pasture availability, once good seasonal conditions returned. Improvements to the simulation model could be achieved by allowing the GRASP pasture-growth model to adjust stocking rates dynamically and more than once a year, and by allowing feedback to GRASP to account for changes in herd dynamics and management.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

This study was co-funded by the Department of Agriculture and Fisheries, Queensland, and the Queensland Government Drought and Climate Adaptation Program. We thank Giselle Whish for conduct of GRASP pasture-growth simulations. We are also grateful to David Reid for conducting statistical analyses. The input of Rob Dixon and Mick Sullivan in setting supplementation rules and responses is greatly appreciated.

References

AgForce (2015) 'Drought survey. Make or break time for assistance. May 2015.' (AgForce Queensland Industrial Union of Employers: Brisbane, Qld, Australia) Available at https://www.parliament.qld.gov.au/documents/committees/AEC/2015/00-bp-03062015-1.pdf [Verified February 2019]

Anderson JR, Dillon JL, Hardaker JB (1977) 'Agricultural decision analysis.' (Iowa State University Press: Ames, IA, USA)

Australian Bureau of Statistics (ABS) (2019) '7503.0 value of agricultural commodities produced, Australia, 2017–18.' Available at https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7503.02017-18?OpenDocument [Verified September 2019]

Beutel T, Silcock J (2008) A report on ground cover and land condition monitoring in the Longreach focus catchment (2005–2007). Appendix 1 of sustainable management of grazing lands in Queensland's rangelands project (monitoring component). State of Queensland, Department of Agriculture and Fisheries, Brisbane, Qld, Australia.

Binswanger H (1980) Attitudes towards risk: experimental measurement in rural India. *American Journal of Agricultural Economics* **62**, 395–407. doi:10.2307/1240194

Bowen MK, Chudleigh F (2017) 'Productivity and profitability of a range of alternative steer growth paths resulting from manipulating the pasture feed base in central Queensland: a modelling approach.' (State of Queensland, Department of Agriculture and Fisheries: Brisbane, Qld, Australia) Available at https://futurebeef.com.au/wp-content/uploads/2018/01/Optimal-cattle-growth-pathways-in-central-Queensland-Bowen-and-Chudleigh-2017.pdf [Verified August 2019]

Bowen MK, Chudleigh F (2018) Grazing pressure, land condition, productivity and profitability of beef cattle grazing buffel grass pastures in the subtropics of Australia: a modelling approach. *Animal Production Science* **58**, 1451–1458. doi:10.1071/AN17780

Bowen MK, Chudleigh F, Whish G, Phelps D (2019) 'Central West Mitchell Grasslands livestock production systems. Preparing for, responding to, and recovering from drought.' (The State of Queensland, Department of Agriculture and Fisheries, Queensland: Brisbane, Qld, Australia) Available at https://futurebeef.com.au/projects/improving-profitability-and-resilience-of-beef-and-sheep-businesses-in-queensland-preparing-for-responding-to-and-recovering-from-drought/ [Verified November 2019]

Bray S, Walsh D, Rolfe J, Daniels B, Phelps D, Stokes C, Broad K, English B, Ffoulkes D, Gowen R, Gunther R, Rohan P (2014) Climate clever beef. On-farm demonstration of adaptation and mitigation options for climate change in northern Australia. Project B.NBP.0564 final report. Meat and Livestock Australia, Sydney, NSW, Australia.

Burrows WH, Orr DM, Hendricksen RE, Rutherford MT, Myles DJ, Back PV, Gowen R (2010) Impacts of grazing management options on pasture and animal productivity in a *Heteropogon contortus* (black speargrass) pasture in central Queensland. 4. Animal production. *Animal Production Science* **50**, 284–292. doi:10.1071/AN09145

Campbell HF, Brown RP (2003) 'Benefit-cost analysis. Financial and economic appraisal using spreadsheets.' (Cambridge University Press: Cambridge, UK)

Cobon DH, Kouadio L, Mushtaq S, Jarvis C, Carter J, Stone G, Davis P (2019) Evaluating the shifts in rainfall and pasture-growth variabilities across the pastoral zone of Australia during 1910–2010. *Crop and Pasture Science* **70**, 634–647. doi:10.1071/CP18482

Commonwealth of Australia (2008) Taking the pulse. Rangelands (ACRIS Management Committee, National land and Water Resources Audit: Canberra, Qld, Australia).

Dixon R (1998) Improving cost-effectiveness of supplementation systems for breeder herds in northern Australia. Project DAQ.098 final report. Meat and Livestock Australia, Sydney, NSW, Australia.

Foran BD, Stafford Smith DM, Niethe G, Stockwell T, Michell V (1990) A comparison of development options on a northern Australian beef property. *Agricultural Systems* **34**, 77–102. doi:10.1016/0308-521X(90)90095-8

Fordyce G, James TA, Holroyd RG, Beaman NJ, Mayer RJ, O'Rourk PK (1993) The performance of Brahman–Shorthorn and Sahiwal–Shorthorn beef cattle in the dry tropics of northern Queensland. 3. Birth weights and growth to weaning. *Australian Journal of Experimental Agriculture* **33**, 119–127. doi:10.1071/EA9930119

Holmes WE, Chudleigh F, Simpson G (2017) 'Breedcow and Dynama herd budgeting software package. A manual of budgeting procedures for extensive beef herds. Version 6.02.' (State of Queensland, Department of Agriculture and Fisheries: Brisbane, Qld, Australia) Available at https://www.daf.qld.gov.au/animal-industries/beef/breedcow-and-dynama-software [Verified July 2020]

Hunt LP (2008) Safe pasture utilisation rates as a grazing management tool in extensively grazed tropical savannas of northern Australia. *The Rangeland Journal* **30**, 305–315. doi:10.1071/RJ07058

Love G (2005) Impacts of climate variability on regional Australia. In 'Outlook 2005. Conference proceedings, climate session papers'. (Eds R Nelson, G Love) pp. 10–19. (Australian Bureau and Resource Economics: Canberra, ACT, Australia)

MacLeod ND, Ash AA (2001) Development of a spreadsheet herd dynamics model to assess the economic value of forecasts in extensive grazing enterprises. Oceans to Farms project report no. 6. CSIRO Sustainable Ecosystems, Brisbane and Townsville, Qld, Australia.

Malcolm B (2000) Farm management economic analysis: a few disciplines, a few perspectives, a few figurings, a few futures. In 'Proceedings of the annual conference of Australian Agricultural and Resource Economics Society'. pp. 1–46. (Australian Agricultural and Resource Economics Society: Sydney, NSW, Australia) Available at https://ageconsearch.umn.edu/bitstream/171920/2/malcolm.pdf [Verified July 2020]

Malcolm B, Makeham J, Wright V (2005) 'The farming game, agricultural management and marketing.' (Cambridge University Press: Cambridge, Melbourne, Australia)

Mayer D (2013) Improved empirical models of cattle growth, reproduction and mortality from native pastures in northern Australia. Project B.NBP.0641 final report. Meat and Livestock Australia, Sydney, NSW, Australia.

Mayer DG, McKeon GM, Moore AD (2012) Prediction of mortality and conception rates of beef breeding cattle in northern Australia. *Animal Production Science* **52**, 329–337. doi:10.1071/AN11204

McCosker T, McLean D, Holmes P (2010) Northern beef situation analysis 2009. Project B.NBP.0518 final report. Meat and Livestock Australia Limited, Sydney, NSW, Australia.

McGowan M, McCosker K, Fordyce G, Smith D, O'Rourke P, Perkins N, Barnes T, Marquart L, Morton J, Newsome T, Menzies D, Burns B, Jephcott S (2014) Northern Australian beef fertility project: CashCow. Project B.NBP.0382 final report. Meat and Livestock Australia, Sydney, NSW, Australia.

McIvor JG (2010) Enhancing adoption of improved grazing and fire management practices in northern Australia: synthesis of research and identification of best bet management guidelines. Project B.NBP.0579 final report. Meat and Livestock Australia, Sydney, NSW, Australia.

McKeon GM, Ash AJ, Hall WB, Stafford-Smith M (2000) Simulation of grazing strategies for beef production in north-east Queensland. In 'Applications of seasonal climate forecasting in agricultural and natural systems: the Australian experience'. (Eds G Hammer, N Nichols, C Mitchell) pp. 227–52. (Kluwer Academic Press: Dordrecht)

McLean I, Holmes P, Counsell D (2014) The northern beef report. 2013 northern beef situation analysis. Project B.COM.0348 final report. Meat and Livestock Australia Limited, Sydney, NSW, Australia.

Nicholls N, Wong KK (1990) Dependence of rainfall variability on mean rainfall, latitude, and the southern oscillation. *Journal of Climate* **3**, 163–170. doi:10.1175/1520-0442(1990)003<0163:DORVOM>2.0.CO;2

O'Reagain PJ, Scanlan JC (2013) Sustainable management for rangelands in a variable climate: evidence and insights from northern Australia. *Animal* **7**, 68–78. doi:10.1017/S175173111100262X

O'Reagain PJ, Bushell J, Holmes B (2011) Managing for rainfall variability: long-term profitability of different grazing strategies in a northern Australia tropical savanna. *Animal Production Science* **51**, 210–224. doi:10.1071/AN10106

O'Reagain P, Scanlan J, Hunt L, Cowley R, Walsh D (2014) Sustainable grazing management for temporal and spatial variability in north Australian rangelands: a synthesis of the latest evidence and recommendations. *The Rangeland Journal* **36**, 223–232. doi:10.1071/RJ13110

Orr DM, Phelps DG (2013) Impacts of utilisation by grazing on an *Astrebla* (Mitchel grass) grassland in north-western Queensland between 1984 and 2010. 1. Herbage mass and population dynamics of Astrebla spp. *The Rangeland Journal* **35**, 1–15. doi:10.1071/RJ11068

Pahl L, Scanlan J, Whish G, Cowley R, MacLeod N (2016) Comparing fixed and inflexible stocking as adaptations to inter-annual rainfall variability in the extensive beef industry of northern Australia. *The Rangeland Journal* **38**, 85–102. doi:10.1071/RJ15045

Phelps DG (2006) Controlling *Aristida latifolia* (feathertop wiregrass) in *Astrebla* spp. Mitchell grasslands with fire and grazing. PhD Thesis, University of New England, Armidale, NSW, Australia.

Quirk M, McIvor J (2003) 'Grazing land management: technical manual.' (Meat and Livestock Australia: Sydney, NSW, Australia)

Rickert KG, Stuth JW, McKeon GM (2000) Modelling pasture and animal production. In 'Field and laboratory methods for grassland and animal production research'. (Eds L 't Mannetje, RM Jones) pp. 29–66. (CABI Publishing: New York, NY, USA)

Robinson LJ, Barry PJ (1996) 'Present value models and investment analysis.' (The Academic Page: Northport, AL, USA)

Rolfe JW, Larard AE, English BH, Hegarty ES, McGrath TB, Gobius NR, De Faveri J, Srhoj JR, Digby MJ, Musgrove RJ (2016) Rangeland profitability in the northern Gulf region of Queensland: understanding beef business complexity and the subsequent impact on land resource management and environmental outcomes. *The Rangeland Journal* **38**, 261–272. doi:10.1071/RJ15093

Scanlan J, McIvor J (2010) Enhancing adoption of best practice grazing management in northern Australia. Phase one: integration and scenario testing. Caring for Our Country Project OG084273. Meat and Livestock Australia, Sydney, NSW, Australia.

Scanlan JC, Pahl L, Whish G, MacLeod N, Cowley R, Phelps D (2011) Enhancing adoption of improved grazing and fire management practices in northern Australia: bio-economic analysis and regional assessment of management options. Project B.NBP.0578 final report. Meat and Livestock Australia, Sydney, NSW, Australia.

Scanlan JC, MacLeod ND, O'Reagain PJ (2013) Scaling up results 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**, 193–200. doi:10.1071/RJ12084

Schatz T (2010) Understanding and improving heifer fertility in the Northern Territory. Project NBP.339 final report. Meat and Livestock Australia, Sydney, NSW, USA.

Star M, Rolfe J, Donaghy P, Beutel T, Whish G, Abbott B (2013) Targeting resource investments to achieve sediment reduction and improved Great Barrier Reef health. *Agriculture, Ecosystems & Environment* **180**, 148–156. doi:10.1016/j.agee.2012.03.016

State of Queensland (2019) 'Land types of Queensland. Version 3.1.' (Queensland Department of Agriculture and Fisheries: Brisbane, Qld, USA). Available at http://www.futurebeef.com.au/knowledge-centre/land-types-of-queensland/ [Verified November 2019]

Teague WR, Kreuter UP, Grant WE, Diaz-Solis H, K'Othmann MM (2009) Economic implications of maintaining rangeland ecosystem health in semi-arid savannah. *Ecological Economics* **68**, 1417–1429. doi:10.1016/j.ecolecon.2008.10.014

VSN International (2017) 'GenStat for Windows.' 19th edn. (VSN International: Hemel Hempstead, UK). Available at https://www.vsni.co.uk/ [Verified July 2020]

Walsh D, Cowley R (2016) Optimising beef business performance in northern Australia: what can 30 years of commercial innovation teach us? *The Rangeland Journal* **38**, 291–305. doi:10.1071/RJ15064

Winks LW (1984) 'Cattle growth in the dry tropics of Australia. AMRC review no. 45.' (Australian Meat Research Committee: Sydney)

Handling editor: Luis Silva